Low-carbon product conceptual design from the perspectives of technical system and human use

Xianfeng Ai[a,b], Zhigang Jiang[b *], Hua Zhang[b] , Yan Wang[c]

[a]Department of art and design, Wuhan University of Science & Technology, Wuhan 430065, China

[b]Hubei Key Laboratory of Mechanical Transmission and Manufacturing Engineering, Wuhan University of Science & Technology, Wuhan 430081, China

[c]Department of Computing, Engineering and Mathematics, University of Brighton, Brighton, BN2 4GJ, United Kingdom

Abstract

Product conceptual design plays a decisive role in carbon emission of the products. Unfortunately, the traditional design methods based on carbon footprint calculation are not suitable for the conceptual design stage, and the latest low-carbon conceptual design research mainly focus on technology development to reduce carbon emissions at the manufacturing stage and less on carbon emissions caused by the unsustainable human use. This makes low-carbon product conceptual design less effective. To address this, a low-carbon conceptual design method is proposed for improving existing products, in which an improved process of requirements elicitation and analysis is implemented firstly, and then the improvement strategies are proposed from the perspectives of technical system and human use to help establish a low-carbon function structure. The conceptual design of a boiling water dispenser is taken as a case study. As a result, 5 low-carbon design strategies and a low-carbon function structure were comprehensively obtained. Next, by calculating the energy consumption of the assumed ideal scenario, it can be found that the re-designed product can save 39.4% energy compared to the existing product in the use stage. The results showed that the proposed method is effective in the generation of low-carbon design schemes at the conceptual design stage.

Keywords: Low-carbon conceptual design; Function matching; Sustainable use; TRIZ laws; Regular expression; Part-of-speech tagging.

1. Introduction

Significant carbon emissions are from the production and use of energy-using products, which leads to serious environmental problems (Bin et al., 2005; O’Connell et al., 2010). Since 80% the environmental impact of products is determined by the design stage (Charter et al., 2001), especially the conceptual design stage (He et al., 2017), it is crucial to consider reducing the carbon emissions of products at the conceptual design stage (Xiu et al., 2012,Cai et al., 2019).

For research in the low-carbon product conceptual design, Song & Lee (2010) presented a low-carbon design system based on the greenhouse gas emissions embedded with bill of materials, which allows designers to identify components with higher carbon emissions easily, and to replace them with better components. Similarly, Peng et al. (2019) proposed a new low-carbon design method based on a multi-layer carbon footprint information model. He et al. (2016) and Zhang et al. (2018) integrated material selection, lightweight technology and carbon footprint calculation to reduce the carbon emission of components of mechanical products. In addition, some studies emphasize the knowledge reuse and its transfer from low-carbon conceptual design to embodiment design (Xu et al., 2013; He et al., 2017). The aforementioned research could help reduce carbon emissions of products from a “technical perspective”, especially the carbon emission generated from the manufacturing of product components. And these have been well understood and used (Li et al., 2019; Ma et al., 2018; Jiang et al., 2019).

However, for the technical perspective, besides the concrete components, the whole function structure of products at a system level also affects the carbon emission of products (Lofthouse et al., 2004). Function structure is one of the main outputs of product conceptual design (Pahl & Beitz, 2007) and the technical system that contains many technical principles (Ulrich & Eppinger, 2014). Thus, there is a need to improve the function structure from the perspective of “technical system” to reduce carbon emissions. Moreover, low-carbon innovation from the “technical perspective” alone does not necessarily lead to emissions reductions (Tang et al., 2012). For energy-consuming products, carbon emissions during use stage may be equal or even exceed those during production stage (O ’connell et al., 2010), and human use has an important impact on this. Good functionality can induce or encourage sustainable use and ultimately reduce carbon emissions in the use phase of energy-using products (Rodriguez et al., 2005). Hence, from the perspective of “human use”, it is also very important to study how to improve the function structure to guide low-carbon use.

Excessive product carbon emissions at the use stage are often associated with two types of problems: 1) the mismatches between delivered functions and desired functions; 2) unsustainable users’ behavior (Wever et al., 2008). So far, there are many studies on “design for sustainable behavior” (De Medeiros et al., 2018), such as “ecological feedback” and “preset script”, which have been proved to be effective (Tang & Bhamra, 2009; Kuo et al., 2018). As for “function matching”, delivered functions can be obtained from the nameplate or manual of the existing product, while users’ desired functions generally need be mined through “requirements elicitation”. For “requirements elicitation”, questions are the key to success. Open questions often get ambiguous responses, while closed questions may limit the participants’ expression (Pohl et al., 2010; Ferrari et al., 2016). To address this, researchers proposed the “controlled natural language” (Pohl et al., 2010). However, participants may still not follow the rules of “controlled natural language” to answer questions. This will result in many invalid responses, which will affect the efficiency of obtaining desired functions. In addition, even if delivered functions and desired functions are obtained, “what to match” and “how to match” are rarely discussed in the existing research (Adeyeye et al., 2017). There is a need for further regarding the content and methods of function matching. Furthermore, when the low-carbon design strategies of “human use” is proposed from “function matching” and “sustainable behavior”, these strategies should be combined with the low-carbon design strategies from “technical system” to achieve a low-carbon function structure.

In order to help establish a more low-carbon function structure, this study proposes a low-carbon conceptual design method, which can help designers put forward low-carbon design strategies from the perspectives of “technical system” and “human use”. Similar to the general conceptual design method proposed by Pahl & Beitz (2007) and Ulrich & Eppinger (2014), this proposed method also includes the “requirements elicitation and analysis” and “function structure establishing”. For the former, low-carbon requirements, the general environment requirements and cost requirements can be obtained from similar literatures. Then, the functional requirements are elicited by a “structured questionnaire” according to the principle of “controlled natural language”, and valid responses are screened out by “Part-of-Speech tagging” and “regular expressions”. For the latter, the product function structure can be constructed according to Energy-Material-Signal (EMS) model (Pahl & Beitz, 2007). Then, on the one hand, since a function structure is a “technical system” supported by a variety of technical principles, TRIZ laws are used to investigate function structure and help designers to propose low-carbon design strategies due to its effectiveness for evolution of technical system. On the other hand, the content and method of function matching are put forward, and the low-carbon design strategies at the “human use” stage are sought from “function matching” and “sustainable behavior”. Finally, all low-carbon design strategies from the perspectives of “technical system” and “human use” are combined to establish a low-carbon function structure.

The remainder of this paper is organized as follows. Related literature is briefly reviewed in section 2. The conceptual method is expounded for low-carbon products in section 3. A case study is shown in Section 4, and finally, the discussions and conclusions are presented in Section 5 and 6respectively.

2. Literature review

A typical conceptual design process general contains at least two steps (Pahl & Beitz, 2007; Ulrich & Eppinger, 2014): 1) requirements elicitation and analysis; 2) function structures establishing. So far, considerable research efforts have been devoted to these two steps.

2.1. Requirements elicitation and analysis for conceptual design

At the conceptual design stage, requirements generally need to be elicited, categorized, and prioritized (Zowghi et al., 2005; Contributor et al., 2015).

As for “requirements elicitation”, some researchers called it “requirements gathering” or “requirements capturing” (Newell et al., 2006), but many other researchers argued that the requirements are elicited rather than just captured or collected (Zowghi et al., 2005). There are many conventional and mature methods of “requirements elicitation”, for example, questionnaires, interviews, workshop, focus groups (Kuhn, 2000; Yousuf et al.,2015). These methods have their own advantages and disadvantages (Zowghi et al., 2005), among them, interviews, questionnaires and scenarios are the most used methods (Pacheco et al., 2018). For questionnaires and interviews, 5W1H is a popular and useful interrogative framework which can be used to elicit a detailed description of the desired function by using who, where, when, what, and how questions (Jabar et al., 2013). These conventional methods, however, may be not applicable in some cases; for example: sometimes it may be difficult to reach the participants of the questionnaires and interviews (Ferati et al., 2016), or question are not answered effectively, even “controlled natural language” may still receive replies that are not useful (Davey et al., 2015).

To address these, researchers have adopted some new techniques based on the Internet, big data mining, and Internet of Things (IOT) technology in recent years. Xu &Li (2011) proposed some gathering strategies for consumer requirements information on the Internet community; Seyff et al. (2015) employed popular social network sites to support requirements elicitation, prioritization and negotiation. Liu et al. (2013) and Qi et al. (2016) put forward different approach to mine user’ requirements from reviews on online shopping platforms. For situations where it is difficult to reach the users, Ferati et al. (2016) argued that IOT technology could be used to enhance traditional methods to solve the problems. These studies provided valuable insights and contributions. However, these still do not support low-carbon product design well. For example, in terms of some production equipment or public energy-using facilities, their purchasers are often dealers rather than users, and the online reviews cannot reflect the requirements of the front-line users well, and in general, the number of online reviews is often scarce. In addition, the above methods are usually used to deal with functional requirements from users, but low-carbon requirements are constraint requirements, which generally come from legislations, such as “Energy Using Products Directive” (EU, 2005), or standards, e.g. “Guide to PAS 2050” (BSI, 2008) and “ISO/TS14067” (ISO, 2013).

For requirements categorizing and prioritizing, requirements are often divided into two categories, functional requirements (FRs) and non-functional requirements (NFRs) (Brace & Cheutet, 2012; Sommerville, 2016). Pohlet al. (2010) pointed out that the term of NFRs is too ambiguous, thus divided it further into quality requirements and constraint requirements. Sudin (2010) found seventeen aspects of requirements. However, excessive categories have led to inevitable coupling between each other, for example, “performance” and “mechanical properties”, “user interface” and “usage” are often related to each other. When requirements have been collected and classified, their priorities and weights need to be determined. For this, researchers used different methods, such as analytic hierarchy process (AHP) and Must-Should-Could-Won’t (MOSCOW) method (Ma et al., 2019; Contributor et al., 2015). Although their methods differ, they all agree on the importance of expert opinion. In summary, the requirements elicitation and analysis for low-carbon product conceptual design needs further research. More stakeholders, e.g. end users, need to be involved, requirements categorizing also need to be further reviewed to reduce the coupling between requirements; and the efficiency of requirements analysis needs to be improved.

2.2. Function definition and function structure establishing

In general, function can be defined from different viewpoints, such as intention viewpoint and system viewpoint. For intention viewpoint, function is the definition of the desired use of the products (Zhao et al., 2003). The intention viewpoint is appropriate for users to describe their desired requirements, thus, is suitable for the product requirements elicitation and analysis (Henderson & Taylor, 1993). For system viewpoint, function is regarded as the relationship between input, output and system state variables. The system viewpoint is mainly applied to the stage for establishing function structure systematically (Zhao et al., 2003). Among all these system viewpoints, Energy-Material-Signal (EMS) model is one of the most famous approaches (Pahl &Beitz, 2007). For an EMS model, a function structure comprises of two parts, the first is the input and output of the Energy-Material-Signal flows between the whole system and the outside world, and the second is the input and output of the Energy-Material-Signal flows between every sub-function (Pahl &Beitz, 2007). Because energy and material are closely related to carbon emission, EMS model is selected for establishing function structure in this study.

To establish a low-carbon function structure, according to the discussion in the section 1, improvement strategies is focused on technical system and human use.

From the perspective of “technical system”, studies on the low-carbon function structure are rare, while product eco-design have been discussed widely. Since low-carbon design is an important branch of eco-design (Ren et al., 2017), most product eco-design takes carbon emission reduction as one of the indicators. These studies about eco-design are partially useful for low-carbon design. In these studies, TRIZ and its combination tools have been widely used. For example, Yang et al.(2011) integrated case-based reasoning and TRIZ method to facilitate preliminary eco-innovation design; Vinodh et al.(2014) combined ECQFD, TRIZ, and AHP to solve sustainable product design problems; Cherifi et al. (2019)developed a new approach named Eca-triz (ecological approach TRIZ), based on a new contradiction matrix. In these studies, the researchers deal mainly with eco-design issues by using contradiction matrix and invention principles of TRIZ. In addition, TRIZ laws of evolution are also widely used in eco-design issues (Yang et al., 2012). Although many tools in TRIZ contribute to product eco-design, TRIZ laws of evolution have systematic characteristics which make it more suitable for the function structure at the conceptual design stage. Moreover, the “Energy conductivity law” can be directly used to investigate the EMS model; hence, TRIZ laws of evolution is well suited to examine the function structure, so as to obtain low-carbon improvement strategies.

From the perspective of “human use”, Wever et al. (2008) argued that sustainable use could be achieved through changing users’ behaviors and matching function. Methods about behavior change usually include “Eco-information”, “Eco-feedback”, “Scripting” and “Forced function” (Bhamra et al., 2011; Tang et al., 2012).These methods follow two principles (Ceschin et al., 2016): 1) Making it easier for users to perform a pro-environmental behavior; 2) Making it more difficult for users to engage in environmentally damaging behavior. For function matching, since QFD-I matrix in Quality Function Deployment (QFD) can correlate “Customer Requirements (CAs)” to the “Engineering characteristics (ECs)” (Hauser and Clausing, 1988), the same principle can be used to transfer low-carbon requirement information into the function structure design (Masui et al., 2003; Bereketli et al., 2013). This means that QFD-I matrix can be used to increase the level of matching between the priority of sub-functions and the priority of requirements. However, the quantitative matching between the parameters of the main function and the actual requirements needs further study.

The literature review shows that, up to now, there are considerable studies devoted to requirements and function structure for product conceptual design. However, for the conceptual design of low-carbon products, the efficiency of requirements elicitation and classification needs to be improved, and the establishment of low-carbon function structure rarely takes into account both the perspectives of “technical system” and “human use”. These make low-carbon conceptual design difficult to be implemented.

3. The low-carbon product conceptual design method

In order to build a low-carbon product function structure from the perspectives of “technical system” and “human use”, a low-carbon conceptual design method is proposed. This method integrates literature method, structured questionnaire, part-of-speech tagging, regular expressions, TRIZ laws of evolution, sustainable behavior and function matching tools into “requirements elicitation and analysis” and “construction of function structure”. The details are shown in Fig.1.

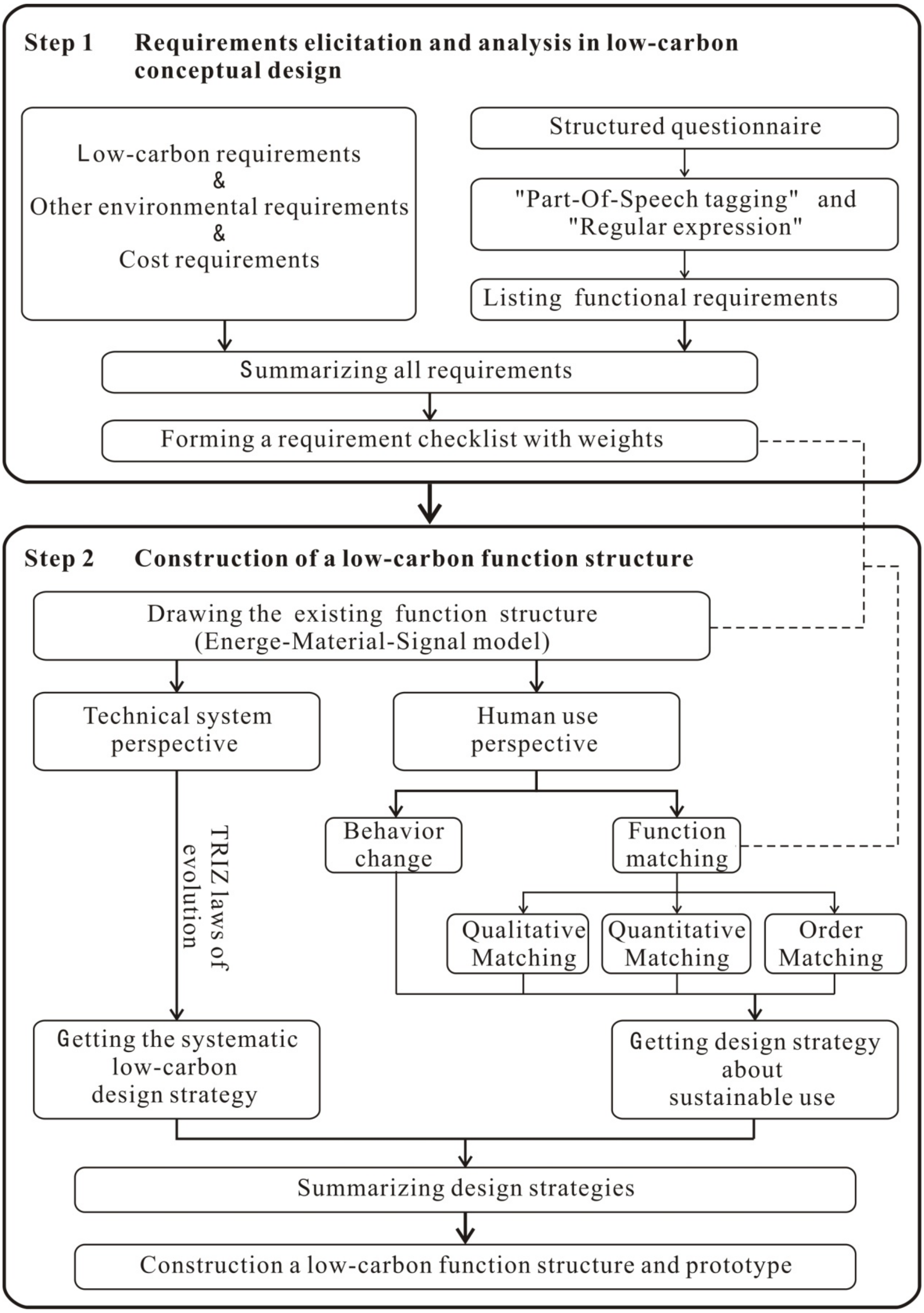

Fig. 1. The conceptual design method for low-carbon products

3.1. Requirements elicitation and analysis in low-carbon conceptual design

According to the research conducted by Brace & Cheutet (2012) and Sudin (2010), the categories of requirements can be set according to four principles: 1) they should be widely recognized in literatures; 2) they can be described at the conceptual design stage; 3) they can cover most of the requirements; 4) they are independent and not coupled to each other. Based on these principles, three categories of requirements are selected, namely the environmental requirements, cost requirements and functional requirements.

Environmental requirements should be subdivided firstly to avoid confusion, because they include low-carbon requirements and other environmental requirements (such as water waste, soil pollution and so on). Referring to Eco-checklist (Brezet, 1997), the environment requirements (Masui et al., 2003), the scope for the product carbon footprint (BSI, 2008) and ISO/TS 14067 (ISO, 2013), the low-carbon requirements and other environment requirements are differentiated and decomposed, which can cover most of environment problems of products. For cost requirements, the acquisition cost and the use-cost should be considered simultaneously as the basis for decision-making. In addition, functional requirements are usually elicited from users.

To understand functional requirements, a two-stage survey is carried out. At the first stage, a qualitative survey of functional requirements and preliminary statistics is conducted. Second, the importance of functions is investigated. For the first stage of survey, since users can generally describe the function as “A product can offer some substances or do something that meet the demand” (Zhao et al., 2003), the questions in the questionnaire are presented in such a structure as shown in *Fig 2*. This structured questionnaire has two advantages: on the one hand, compared with choice questions, it allows users to express functional requirements freely; on the other hand, compared with essay questions, it can diminish the ambiguity of human language and reduce the difficulty of information processing.

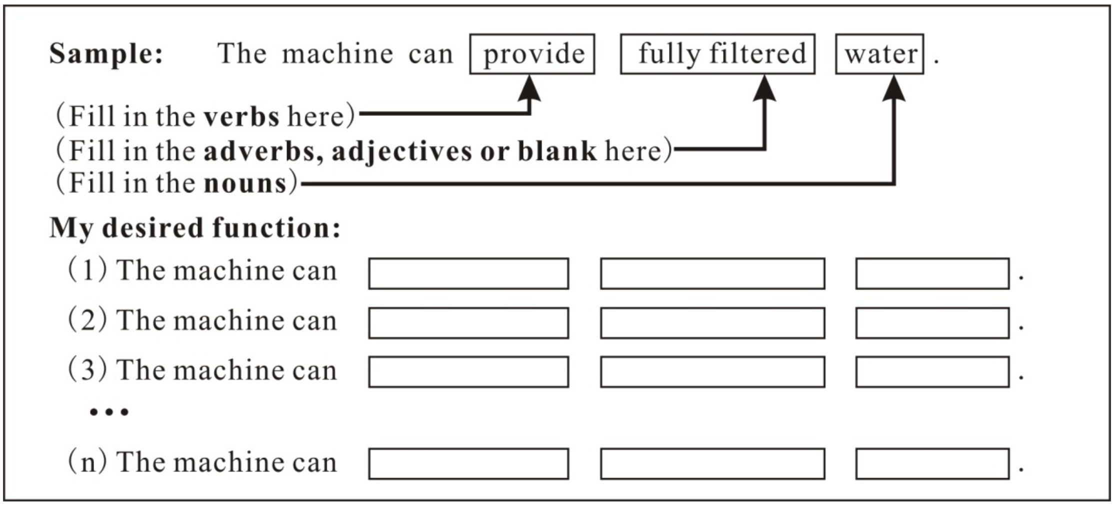

Fig. 2. The structured questionnaire

In addition, at the top of the questionnaire, 5W1H method is introduced to inspire users (Jabar et al., 2013). “Who” question is a basic element of a function, and it could involve users, owners and other stakeholders of the product. “Where” describes location information about users and functions when users interact with product functions. “When” represents all kinds of time information. “What” indicates the detailed parameters of functions, for example, temperature, volume, force, flow rate, etc. “Why” refers to intention of users or other stakeholders. At last, “How” is related to users’ behaviors.

Then, the questionnaire is published on an online platform. Finally, statistical analysis can be performed after the response has reached the expected volume. Statistical analysis consists of two steps. First, a tool capable of Part-of-Speech tagging is used first (Cheet al., 2010), and the Regular Expressions in EXCEL VBA is employed for retrieval and matching. By performing this step, the valid questionnaires can be identified. Second, the designer can sort out the desired functions of users and list them in a table.

Next, the weights of all requirement items (*Table* 1) should be determined. It can be done in two steps. In the first step, according to the valid questionnaire, calculate the frequency of each functional requirement item mentioned, and sum up. In this way, the weight of each functional requirement item in the total functional requirement items can be calculated. In the second step, according to the five-point scale of Likert (Likert, 1932), 5 experienced eco-design experts are invited to determine the weights of 7 indicators, includingC_1 to C_6 (in *Table* 1) and the entire functional requirements C_7. Finally, opinions of all experts are aggregated to calculate the mean value, and combined with the results of the first step, and then, the weights of all requirements items can be obtained.

Table 1 Requirements checklist for low-carbon product design

Requirement categories	**Requirement items**	**Weight**	**References**
Low-carbon requirements	C_1: Less energy consumption.	W_1	Masui et al.,2003 BSI, 2008 ISO14067, 2013
	C_2: Less resource consumption.	W_2	
Other environmental requirements	C_3: Easy to recycle, reuse.	W_3	
	C_4: Less emission of toxic substances.	W_4	
Cost requirements	C_5: Acquisition cost.	W_5	Dieter, 2000 Ullman, 2002 Pahl & Beitz, 2007 Sudin et al, 2010
	C_6: Use-cost.	W_6	
Functional requirements	C_7: (according to the questionnaire)	W_7 … W_n	

3.2. Construction of a low-carbon function structure

At this step, according to EMS model, the function structure of an existing product should be drawn first. Then it can be inspected from the perspectives of “technical system” and “human use”, mainly for exploring low-carbon design strategies, while other design strategies will be obtained at the same time according to traditional approach which is not discussed in this paper.

3.2.1. Improvements from "Technical system" perspective

As greenhouse gas emissions are usually associated with energy consumption, thus energy flow can generally be considered directly related to the low-carbon requirements. It should be noted that the carbon emissions from human doing manual work are not counted (BSI, 2008).For example, manual juicers or bicycles, when these products are used, there are human-induced energy flows, but these products do not produce carbon emissions. Except human-induced energy flow, other energy flows are considered to be related to carbon emissions. Material flows and signal flows in product affect the carbon emission by affecting the energy flows. Hence, after the function structure is drawn based on EMS model, it can be systematically improved from the aspects of Energy-Material-Signal flows with a focus on the energy flow. According to TRIZ laws, common improvement measures for energy efficiency are as follows (Tan, 2010):

- using more environmentally friendly energy;
- improving energy conversion efficiency;
- reducing the number of energy form conversions;
- reducing the number of energy transfers.

By following these measures, unnecessary energy losses in the existing function structure can be identified, and systematic strategies for improvement can be proposed.

3.2.2. Improvements from "Human use" perspective

Discussing low-carbon design from the perspective of "human use" means to reduce carbon emissions by inducing "sustainable use". In terms of "sustainable use", improvement strategies are proposed from "function matching" and "behavior change" (Wever et al., 2008).

Since there is less discussion on "function matching", in this study, the detailed content of function matching is discussed, and a method of "function matching" is proposed, which contains qualitative matching, quantitative matching and order matching.

On qualitative function matching, the existing EMS model is compared with the requirements items in *Table 1*. If a desired function (i.e., a requirement item) has the corresponding delivered function, it is marked as "Y", otherwise, "N". If a delivered function does not exist in the desired functions, check if it is redundant, or if it meets a potential requirement beyond the description by users. Finally, the items marked with "N" and with high weight are taken as the key improvement objects of the function structure.

In terms of quantitative matching of key functions, the designers need to select the requirement items in *Table 1*which are heavily weighted and marked as "Y", and then list some parameters associated with them. Two points need to be emphasized: (1)

these parameters must be able to be assigned a metric data (or interval) rather than categorical and rank data, because only metric data is quantitative data; (2) these parameters are not EMs in QFD, because they are user-oriented. EMs are generally technical parameters of products and are engineers-oriented. Most users are unfamiliar with EMs. For example, users are more concerned about “how long does it take the machine to make an ice cream” than “what is the power or energy efficiency ratio of the machine”.

In order to obtain the desired value of these parameters, a variety of survey methods can be used, such as field observation or general questionnaire survey. At the end of the investigation, the average interval or average value of these physical quantities can be calculated.

Then the desired value is compared with the delivered value of the existing product. The desired value of the *i*th parameter is denoted as DS_i, and the delivered value of the corresponding *i*th parameter is denoted as DL_i. These two values are generally one or more ordered interval sets, and their matching relationships have the following three possibilities, as shown in *Fig.3*: (1) Partial match; (2) Complete match; (3) Complete mismatch.

The formula for calculating the matching degree of the *i*th parameter is as follows:

$$M_i = \frac{L(DS_i \cap DL_i)}{L(DS_i \cup DL_i)} \quad (1)$$

If the DS_i and DL_i belong to interval scale data, $L(DS_i \cap DL_i)$ represents the total interval length of the intersection of the *i*th desired parameter and the *i*th delivered parameter; and $L(DS_i \cup DL_i)$denotes the total interval length of the union of the *i*th desired parameter and the *i*th delivered parameter. If the DS_i and DL_i belong to ratio scale data, the smaller value in DS_i and DL_i is assigned to $L(DS_i \cap DL_i)$, and the higher value in DS_i and DL_i is given to $L(DS_i \cup DL_i)$.

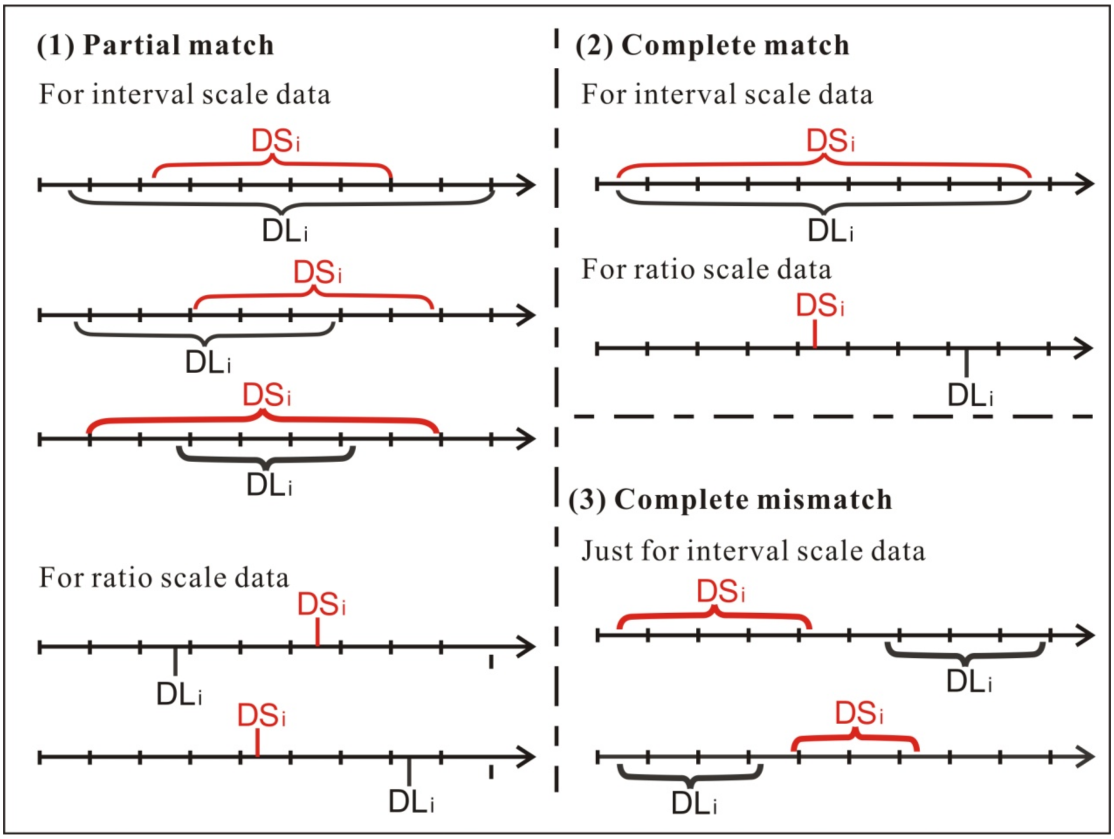

Fig.3 Three types of function parameter matching

After calculating the matching degree, the parameters with low matching degree should be improved primarily.

With regard to the functional order matching, QFD-I matrix needs to be performed, the requirements (CAs) and weights are firstly filled into the relevant columns on the left side of the QFD-I matrix *(Table 2)*. The Engineering Characteristics (ECs) are determined by designers according to requirements and specific products. Seven general low-carbon ECs can be summarized according to previous researches (Masui et al., 2003; BSI, 2008; ISO14067, 2013), as follows:

(E_1) weight.
(E_2) volume.
(E_3) number of parts.
(E_4) the complexity of material.
(E_5) the low-carbon property of the recovery method.
(E_6) amount of energy consumption in its life cycle.
(E_7) amount of resource consumption in its life cycle.

Similarly, other ECs also need to be assigned by designers according to a specific product, and then all ECs are filled into the upper part of the matrix. Then, a matrix can be created and filled according to the weights of CAs and the “relational strength” of ECs and the CAs, and the weights of ECs can be calculated accordingly.

Table 2QFD-I matrix

CAs	weight	E_1	E_2	E_3	...	E_k
C_1	w_{c1}					
C_2	w_{c2}					
C_3	w_{c3}					
...	...					
C_j	w_{cj}					
Row score						
Weight of each ECs						

Through the calculation of QFD-I, the relative importance of desired functions (i.e., CAs) can be inherited by ECs, so the matching of importance degree ordering can be achieved. It enables more resources to be allocated to the most important requirements in design and development. In addition, since the importance of each EC is obtained, the evaluation after design can be more accurate.

On behavior change for "sustainable use", designers need to observe user's behavior, and find out the bad behavior of wasting energy and resources in the process of use. Appropriate "behavior change design" methods or principles mentioned in section 2.2 are then used to improve the function structure to inhibit or eliminate these undesirable behaviors.

When the tasks above are completed, design strategies from all perspectives can be integrated to construct a low-carbon function structure.

4. Implementation example

In order to verify and demonstrate the presented conceptual design method, it is used to redesign an existing product. A boiling water dispenser for teaching building is selected as case study because low-carbon properties were not considered in its original design.

4.1. Requirements elicitation and analysis in the boiling water dispenser design

At the first stage, the requirements checklist is identified. The cost requirements and environment requirements are determined according to Table 1, and the functional requirements are extracted from the questionnaire survey.

At the first stage of the survey, 753 people were invited to answer the online structured questionnaire, including 748 users, 2 managers and 3 maintainers. Afterwards, 612 questionnaires were collected, including 2,473 functional requirements, while another 141 participants failed to respond to the questionnaire. Then, Ltp-3.2.0 (Che et al., 2010) was used for Part-Of-Speech tagging of the collected questionnaires. Verbs will be marked as "/v", adverbs "/d", adjectives "/a", and nouns "/n", and auxiliary words "/u", and then the following regular expressions were used to retrieve and match. These regular expressions conform to the expression logic in Chinese, and its pattern and logical relationship is shown in *Fig.*4.

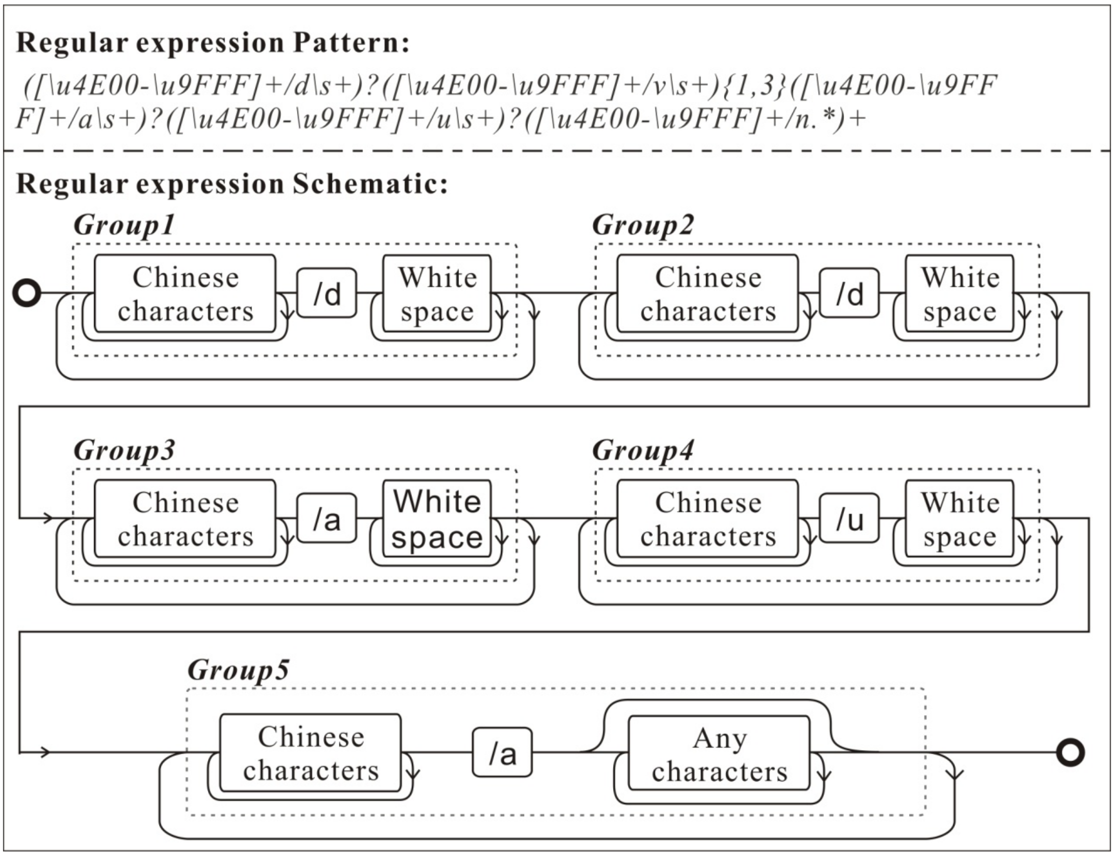

Fig.4. The regular expression to retrieve and match

Then, 1488 mismatched items were deleted, and the rest985 functional requirements were combined by the designer team, in the process, for a few obscure items, the designers consulted the users again to find out their real purposes. The main tasks of these combination activities are merging and deleting. Similar ones were merged, and requirements that go beyond the definition of this product can be removed, such as “It can provide coffee and juice”; “It can provide ice water”; or “It can provide a sink for hand washing”, etc. Finally, 20 requirement items were listed in the Table 3.Further explanations of some of these items are as follows: regarding items (7), (8) and (11), users refer to the scenario where they want the boiling water but only get the warm water, or the machine stops supplying water until it boils. As for item (13), many users pointed out that most of the boiling water machines are located next to toilets, and they often take boiling water during the break and on their way to the toilets. Therefore, they hope that there is a place to put cups near the boiling water machines to avoid the embarrassment of bringing cups into toilets. Although this requirement has nothing to do with reducing carbon emissions, the low-carbon design shall address the general functional requirement, and it is also widely mentioned, so we think it should still be included. In terms of items (18) and (20), they both involve the problem of waiting in queues at peak periods to get the boiling water.

After the collation of the research results, experts are invited to score these research results according to the method detailed in section 3.1, the final weight of every item is shown in the third column of Table 3.

Table 3 Requirements checklist about a boiling water dispenser

Requirement categories	Requirement items	Weight	Match
Low-carbon requirements)	C_1: Less energy consumption.	W_1=0.101	---
	C_2: Less resource consumption.	W_2=0.085	---
Other environment requirements	C_3: Easy to recycle, reuse.	W_3=0.041	---
	C_4: Less emission of toxic substances.	W_4=0.032	---
Cost requirements	C_5: Acquisition cost.	W_5=0.041	---
	C_6: Use-cost.	W_6=0.069	---
Functional requirements	C_7: It can display the temperature of water.	W_7=0.034	Y
	C_8: It can display the amount of water.	W_8=0.033	Y
	C_9: It can provide warm potable water.	W_9=0.053	N
	C_{10}: It can provide boiling potable water.	W_{10}=0.06	Y
	C_{11}:It can provide boiling water rapidly.	W_{11}=0.057	Y
	C_{12}: It has no incrustation and germs.	W_{12}=0.036	Y
	C_{13}: It has room for cups.	W_{13}=0.042	N
	C_{14}: It can reduce the splash of boiling water.	W_{14}=0.05	N
	C_{15}: Its faucets should have anti-scald function.	W_{15}=0.043	N
	C_{16}: It does not boil the same pot of water repeatedly.	W_{16}=0.045	N
	C_{17}: It provides enough faucets.	W_{17}=0.063	Y
	C_{18}: It provides warm water for washing cups.	W_{18}=0.053	N
	C_{19}: It has its own dustbin for storing waste such as coffee bags or tea bags.	W_{19}=0.022	N
	C_{20}: Users can reserve boiling water through their mobile phones.	W_{20}=0.04	N

4.2. Construction of a low-carbon function structure for the water dispenser

First, the function structure diagram of the existing water dispenser is drawn (as shown in *Fig.*5), and then, the improvements are sought from two perspectives.

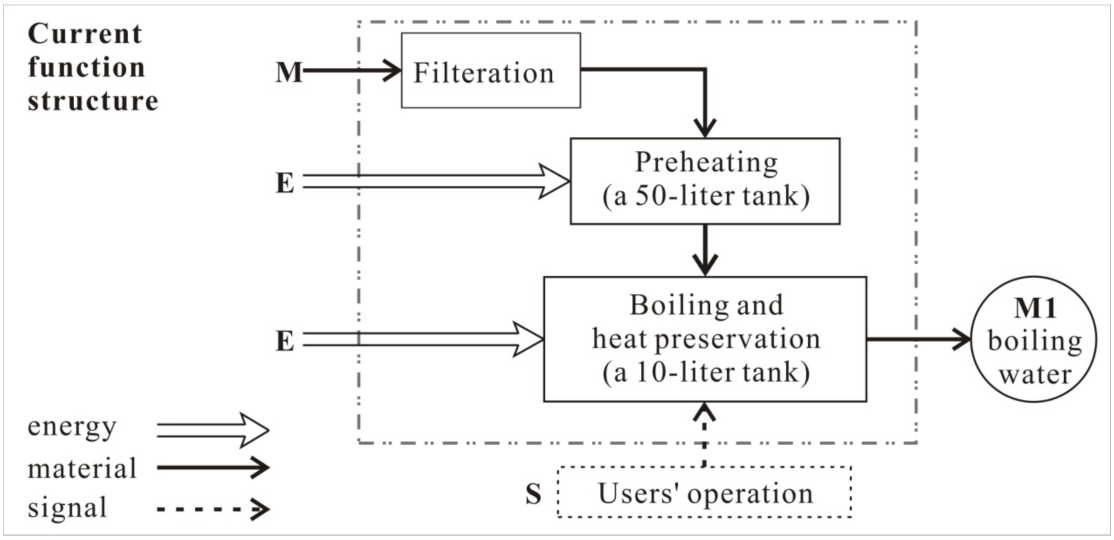

Fig. 5. The existing function structures

4.2.1. From "Technical system" perspective

According to *Fig.5* and the specifications of the case study water dispenser, water is initially filtered and then flows into a 50-liter tank in which it is preheated. Next, the preheated water flows into a 10-liter tank, where it is boiled and insulated. In the light of the improvement measures mentioned in 3.2.1, the problems of the function structure can be listed:

- This water dispenser is sterilized by boiling, which has high-energy consumption and can be improved utilizing other methods, such as "ultraviolet sterilization";
- Machines only provide boiling water, which is not convenient for people who need warm water, and it is a waste of energy. It can be improved by "heating directly to the required temperature" to reduce energy loss;
- Although both tanks have thermal insulation function, energy loss still exists, especially when the frequency of use is low. Therefore, the ideal situation is that the machine only heats water, but do not store water.

4.2.2. From "Human use" perspective

Regarding the qualitative function matching for the boiling water dispenser, the functions in Fig.5 are compared with the 20 functional requirements listed in Table 3. And then the matching results are calculated and listed in the fourth column of Table 3 which suggested that the water dispenser cannot meet the needs of C_9, C_{18}, C_{14}, C_{16}, C_{15}, C_{13}, C_{20} and C_{19} at present. Hence, the function structure of this product shall be improved to meet these needs, especially the top-ranked items.

Next, the quantitative matching of key functions is performed. The requirement items C_9, C_{10},C_{11} and C_{17} in Table 1 were selected, and then the following four parameters were listed after the analysis.

1) acceptable waiting and operating time (total time from queuing to fetching water);

2) desired temperature ranges (the temperature of the drinking water that the users desire);
3) desired number of faucets.
4) number of people fetching water at different time ranges.
By comparing the investigation results with the actual situation, the final matching results are shown in Fig 6.Where the DS_i refers to the specific parameter value or interval of desired requirements, the DL_i refers to the actual parameter value or interval of the function delivered.

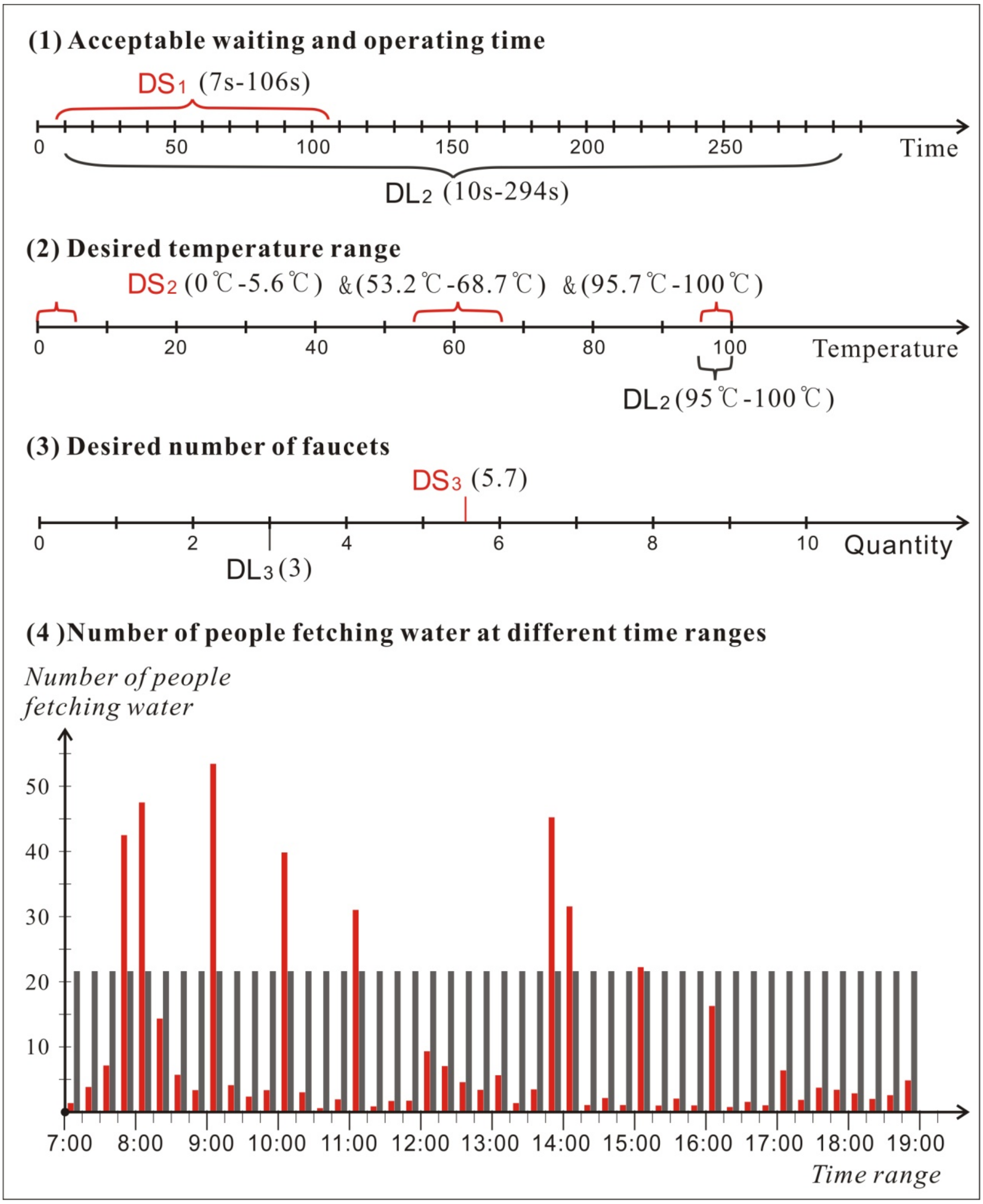

Fig .6. Matching results

As shown in *Fig.6*, the matching degree of the first three parameters can be calculated (M_1=0.349; M_2=0.164; M_3=0.526).

The fourth parameter is set to calculate the matching degree of “number of people who have the time to fetch water” and “number of people who actually fetch water”. For this, according to the schedule of the teaching building，a quarter of an hour is selected as a time range for statistics, and the average number of people fetching water per quarter of an hour between 7:00 and 19:00 was counted.

The specific investigation was carried out on 17 working days, and the use of the same type of machine in different teaching buildings was counted. Finally, the average number of people in each time range of 17 days was calculated and assigned to DS_4. Thus, DS_4 is an array of 48 numerical values. DL_4 is also an array with 48 numerical values, which means “the number of people who fetch water in a quarter of an hour”. According to the experimental observation and statistics, when there are enough people in line, 22 people can get water within acceptable time (106 seconds) in every quarter of an hour, so all the values in the DL_4 array are 22. The values for all DS_4 and DL_4 are shown in the fourth coordinate diagram of *Fig.*6. For DS_4, the values of the time range No.4, No.5, No.9, No.13, No.17, No.28, No.29 and No.33 are large, which are 43.1, 47.9, 53.5, 39.8, 31.2, 45, 31.3 and 22.8 respectively. The other 40 values of DS_4 will not be listed due to limit of space. The matching degree M_4 which is the average of 48 periods is then calculated as M_4=0.249.

From the values of these four matching degrees, there is a room for improvement in these aspects of the product, especially the second and fourth parameters.

Functional order matching is the last step in functional matching. Seventeen Engineering characteristics (ECs) are ascertained firstly. E_1 to E_7 have been described in the section 3.2.2, and they are related to low-carbon properties. Other 11ECs are specific items for the boiling water dispenser, and are confirmed by the experts after several rounds of interviews, they are listed as follows:

(E_8) the total price of filter core in a certain period.
(E_9) the cost of production.
(E_{10}) structure design level.
(E_{11}) heating energy efficiency ratio.
(E_{12}) filtering speed and grade.
(E_{13}) bactericidal ability.
(E_{14}) insulation capacity of faucet material.
(E_{15}) intelligent level (including temperature control, information display and operation feedback, etc.).
(E_{16}) heating power.
(E_{17}) the amount of water heated each time.
(E_{18}) water flow rate of at faucet outlet.

Then, QFD-I procedure is carried out by designers and engineering experts. In the *Table 4*, the correlations of CAs and ECs are assigned null, 1, 3, and 5. Among them, null means “irrelevance”, 1 represents “weak correlation”, 3 refers to “general correlation”, and 5 expresses “strong correlation”.

Table 4 QFD-I of a boiling water dispenser

CAs	weight	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8	E_9	E_{10}	E_{11}	E_{12}	E_{13}	E_{14}	E_{15}	E_{16}	E_{17}	E_{18}
C_1	0.101	3	3	1	1	1	5	3			1	5	1			3		3	
C_2	0.085	1					5	1			1		3						
C_3	0.041			3	5	3	3						3						
C_4	0.032	1	1		3	5	1												
C_5	0.041	1	1							5			3			3	1		
C_6	0.069								5			5	1			3			
C_7	0.034															5			
C_8	0.033															5			
C_9	0.053												5	5		5			
C_{10}	0.06												5	5		5			
C_{11}	0.057											3	3			3	5	3	3
C_{12}	0.036												5	5					
C_{13}	0.042	1	3								5								
C_{14}	0.05										5								5
C_{15}	0.043														5				
C_{16}	0.045															3		5	
C_{17}	0.063		3														3	3	3
C_{18}	0.053		3								5					5			
C_{19}	0.022	1	3								5								
C_{20}	0.04															5			
Raw score		0.53	0.92	0.22	0.4	0.38	1.09	0.39	0.35	0.21	1.02	1.02	1.59	0.74	0.22	1.85	0.52	0.89	0.61
Weight of each ECs		0.04	0.07	0.02	0.03	0.03	0.08	0.03	0.03	0.02	0.08	0.08	0.12	0.06	0.02	0.14	0.04	0.07	0.05

Through the calculation of QFD-I, the designer converts the importance of users’ requirements into the importance of engineering parameters of the product. Table 4 shows that (E15), (E12), (E6), (E10), (E11), (E2), and (E17) is relatively important, which should be given special attention in conceptual design and subsequent design.

Finally, low-carbon design strategies need to be sought from sustainable behavior. Through the investigation and observation of the process of how people use the products, some behaviors that lead to unnecessary energy or resource consumption are identified. Specifically, problems were found such as: as the machines can only provide boiling water and cold water, so many users use boiling water to wash the cup, and cold water is rarely used because it is considered to be un-hygiene by users that believe that the high temperature of boiling water can kill germs. All these lead to the waste of thermal energy. In order to reduce this unnecessary energy consumption, some behavior change design methods are used to give design advice, such as:

- In the product appearance partition, the sink and the warm water tap can be designed on the same side to guide the user to use warm water to clean the cup, so as to avoid the waste of energy caused by the use of boiling water to wash the cup;
- Display some information on the appearance, such as the life of the filter element, and inform users that all water is thoroughly filtered and sterilized.

When all the steps above are completed, these recommendations and strategies are integrated to improve the original design. The redesigned function structure and prototype are showed in Fig 7. It has the following features:

1) It improves the level of filtration and sterilization. The original machine uses boiling method to sterilize and precipitate impurities in water, which can be replaced by a more energy-saving way to achieve a higher level of filtration and sterilization.

2) It provides both boiling water and warm water. It not only brings convenience to users, but also avoids wasting energy for those who only need warm water, because boiling water consumes more energy than getting warm water.

3) Two heating modes are available. The first is “instant heating”. When the user operates the button, the machine heats the water in a 500ml container at room temperature to the temperature range required by users. And the second is “scheduled time heating”, which can boil the water inside a 50-liter container at a predetermined time, to meet peak requirement and reduce queuing times. This can improve the matching degree between supply and requirement in different time periods, and save energy.

4) “Warm water” is obtained directly by heating, rather than boiling first and then cooling. This can save energy.

5) In the prototype diagram, the area marked as “1” only provides normal temperature water. This area has a large space and a sink that can guide the user to wash the cup in order to reduce the excess energy waste caused by the user using boiling water to wash the cup. In the area marked as “2”, 3 faucets can provide both boiling water and warm water, and its countertop is high, to avoid the cup is too far from the faucet and cause boiling water splash. The area marked as “3” provides a place to put the cup, meeting the needs for users to keep the cups next to the dispenser on their way to toilet. In addition, at the later design stage, according to the “Eco-feedback” in the principle of sustainable use (Tang et al., 2012), some information can be set in the four screens (in blue color on top of faucets) at the top of the prototype to motivate

people to save water and energy.

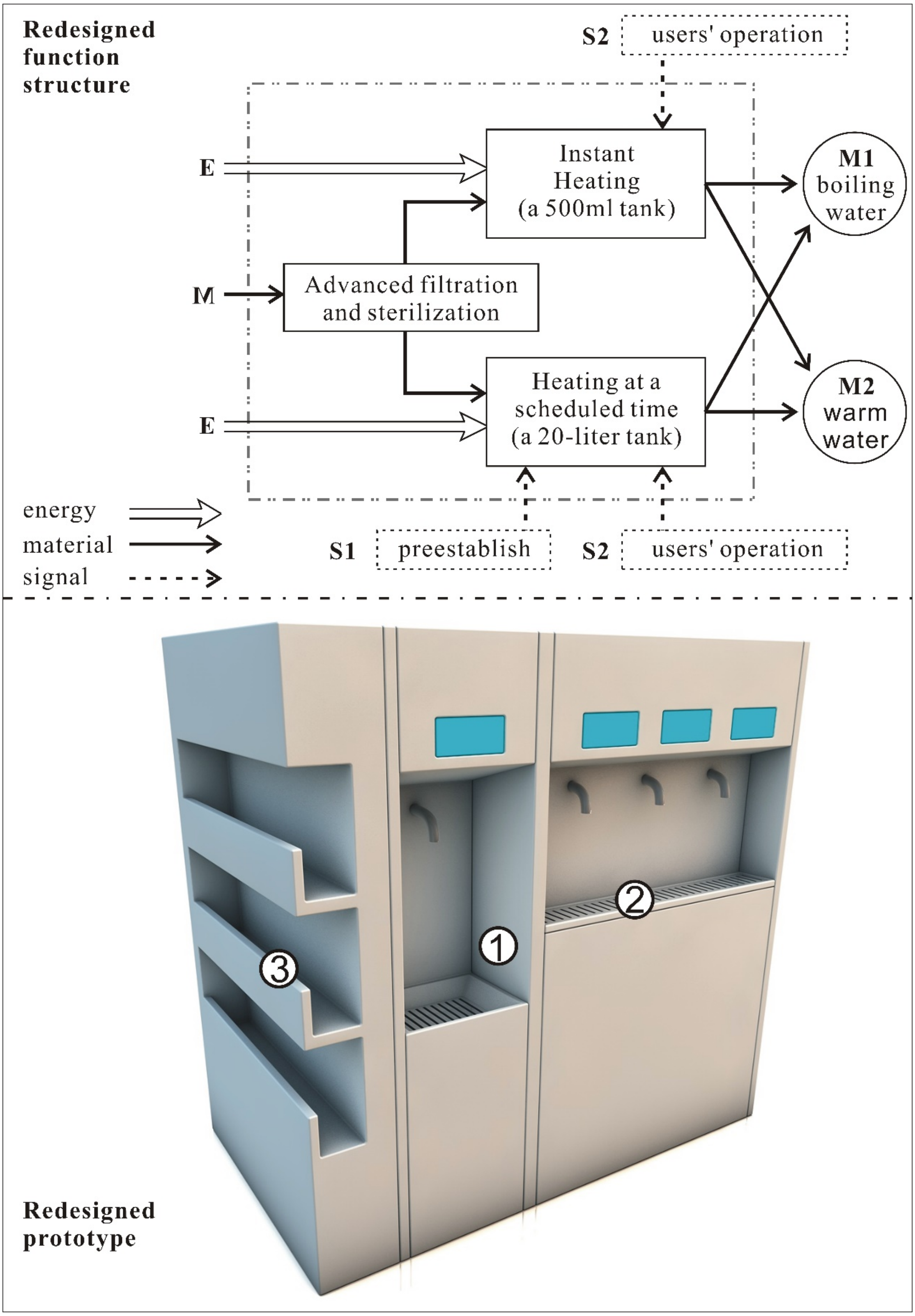

Fig. 7. Redesigned function structure and prototype

5. Result and Discussion

This study aims to propose a low-carbon design method suitable for the product conceptual design stage. It was found that it is feasible to carry out low-carbon design at the conceptual design stage. The function structures can be improved from the perspectives of technical system innovation and sustainable use. The energy saving using the proposed new prototype design can be calculated as below:

According to Fig.6, the average number of people fetching water per day on each machine is 463.6. Assuming that 0.5kg of water is taken per person (i.e., 500ml), the total water intake is 231.8kg. Assuming that 30% of the users use water to wash the cup with 0.5kg of water per person, 69.54 kg of water is used for this purpose.

Assuming that the machine is under normal temperature and pressure (25℃,101kpa), the Specific Heat Capacity of water in this state is 4.2×10^3J/(kg·℃).

The existing water dispenser consumed electricity in three parts during a day:
1) theoretical energy consumption of drinking boiled water is as follows:

$$\frac{231.8kg*(100℃-25℃)*4.2*10^3 \mathrm{J/(kg\cdot ℃)}}{3600000J/KW\cdot H} = 20.28\mathrm{KW\cdot H};$$

2) the water consumption of 30% of people to wash the cup is as follows:

$$\frac{69.54kg*(100℃-25℃)*4.2*10^3 \mathrm{J/(kg\cdot ℃)}}{3600000J/KW\cdot H} = 6.08\mathrm{KW\cdot H};$$

3) assuming that the water temperature dropped by an average of 15℃ over each time range (15 minutes) and then the water was boiled again. According to Fig.6, 7.574kg of water is left on average in 40 time ranges every day. The consumption for repeated boiling is as follows:

$$\frac{40*7.574kg*15℃*4.2*10^3 \mathrm{J/(kg\cdot ℃)}}{3600000J/KW\cdot H} = 5.3\mathrm{KW\cdot H};$$

The total power consumption per day of existing water dispenser is 31.67 (KW·H).

For comparison, the redesigned water dispenser consumed electricity in three parts during a day:
1)assuming that 60% of users need boiling water (100℃) and the other 40% need warm water (60℃). Then the available power of this part is as follows:

$$\frac{0.6*(100℃-25℃)+0.4*(60℃-25℃)}{100℃-75℃} * 20.28KW\cdot H = 15.96\mathrm{KW\cdot H};$$

2) assuming that 15% of all users change their behavior and use cold water to wash the cups. The water consumption for washing the cup will be halved to only 3.04 KW·H;
3) assuming that the machine will pre-boil the water in the 20-liter container only when the number of people fetching water is more than 20. In other cases, instant heating is adopted. According to Fig 6- (4), considering the water consumption of those 15% who are still washing the cup with boiling water, there will be only 3 time ranges (11:00-11:15,14:00-14:15,15:00-15:15) when there is excess boiling water. The consumption for repeated boiling is as follows:

$$\frac{(60-((31+31.5+22.8)*1.15*0.5))kg*15℃*4.2*10^3 J/(kg\cdot℃)}{3600000 J/KW\cdot H}=0.19KW\cdot H;$$

The total power consumption per day of redesigned water dispenser is 19.19 (KW·H).

It can be seen that, under the theoretical scenario, the re-designed product prototype can save 39.4% of the electric energy compared to the original design in the use process.

It was found that the proposed method for requirements elicitation and analysis can collect the requirements from various stakeholders, which is consistent with the research goals suggested by Xu et al. (2015). Regarding the requirements elicitation and analysis, the combination of “structured questionnaire”, “Part-Of-Speech tagging” and “regular expression” can be used to elicit and analyze users’ requirements effectively. Compared with the traditional Internet based research method (Xu &Li, 2011), the structured questionnaire method proposed can collect more accurate data. On the one hand, it can reduce the errors caused by improper questionnaire design; on the other hand, it can also avoid the distraction from the answers from respondents that are not aligned with the purposes of the questionnaire. Compared with those methods using big data mining technology (Liu et al., 2013; Qi et al., 2016),the method proposed is more suitable for requirements elicitation of production equipment and public energy-using facilities, since the buyers of these products are not users, and there is insufficient information to be mined and analyzed. In addition, the current low-carbon requirements generally come from governments or other public sector organizations, rather than end users. In addition, compared with the methods using IOT technology (Ferati et al., 2016), this method proposed in this paper is easier to popularize.

In addition, unlike those methods for replacing high-carbon components (Song & Lee, 2010; Lu et al., 2018), this study tends to improve the overall function structure, which is more macro, systematic and suitable for the conceptual design.

The case study results showed that the proposed function matching algorithm is simple and effective, and it can help to propose low-carbon design strategy. In contrast, the matching algorithm proposed by Yang et al. (2016) is relatively macro, which is the matching of enterprise-level requirement and service, and is not applicable to the function matching at specific product level. Adeyeye et al. (2017) discussed the causes of function mismatch, but did not give specific matching methods. This study proposes a function matching method, which are applicable to a variety of data, enabling the matching calculation between interval number and single value. This makes it suitable for a variety of design scenarios.

6. Conclusions

It is a difficult task to implement low-carbon product design at the conceptual design stage. For this, a low-carbon conceptual design method is proposed in this paper. The method consists of two steps, “requirements elicitation and analysis” and “construction of a function structure”. This method is verified by a low-carbon conceptual design of a boiling water dispenser. In this case, five low-carbon design strategies and one low-carbon function structure were proposed. Moreover, it can be found that the re-designed product can save 39.4% energy than the existing product at the use stage in the assumed ideal scenario. This shows that this method is indeed helpful to inspire a number of low-carbon design strategies at the conceptual design stage.

Compared with similar existing researches, the value of this method lies in the following four points: 1) This method can help designers put forward low-carbon design strategies from the perspective of technical system and human use, and establish a new low-carbon function structure; 2)In terms of the design of public energy-using products, requirements elicitation and analysis in this method have more advantages than other methods; 3) Using TRIZ laws to examine Energy-Material-Signal model can reduce energy consumption at the system level;4) The proposed function matching method can help reduce the extra energy consumption caused by function mismatch.

The future work could be conducted in the following areas: 1) establish the physical model of boiling water machine, calculate the energy consumption and carbon emission in the process of use under real use scenarios, and further verify the method proposed in this paper; 2) gather the energy consumption data and human use data of boiling water machine, and then investigate the relationship between energy consumption and human use. Finally, form a data-driven low-carbon conceptual design method.

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