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A function-based computational method for design concept evaluation

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ABSTRACT

Concept generation is an indispensable step of innovation design. However, the limited knowledge and design thinking fixation of designers often impede the generation of novel design concepts. Computational tools can be a necessary supplement for designers. They can generate a big number of design concepts based on an existing knowledge base. For filtering these design concepts, this work presents a computational measurement of novelty, feasibility and diversity based on 500,000 granted patents. First, about 1700 functional terms (terminologies) are mapped to high dimensional vectors (100 dimensional space) by word embedding technique. The resulted database is knowledge base-I (KB-I). Then, we adopt circular convolution to convert patents into high dimensional vectors. The resulted database is KB-II. Based on the two knowledge bases, the computational definitions of novelty, feasibility and diversity are developed. We conduct six experiments based on KB-II, a random dataset and a real product dataset, and the results show that these metrics can be used to roughly filter a big number of design concepts, and then expert-based method can be further used. This work provides a computational framework for measuring the novelty, feasibility and diversity of design concept.

1. Introduction

Concept generation is the most creative and an indispensable step of innovation design. Many researchers have stated that there is a significant correlation between the quality of design concepts and success of final products [4,12]. However, improving the quality of design concepts is not easy, since it largely depends on designers' design thinking process, which is often limited by designers' knowledge and design thinking fixation [23,13]. Therefore, using external knowledge and assistance tools becomes one of the ways to improve the quality of design concepts [12].

The assistance tools for concept generation can be briefly categorized into two branches, including structured method and computational method. The structured method adopts a structured process as guidance for generating design concepts. There are already some typical structured methods. The 6-3-5 [24] method and C-Sketch [26] ensure a group of designers participate into a design process equally. The design-by-analogy [16] and function-mean trees [15] are function-based structure method, and both methods obey the principle of "decomposing function ⇒ finding solution ⇒ integrating solutions". The computational method is a relatively new research direction of generating design concepts, and existing methods are not as many as structured method. Kurtoglu extracted 45 rules of generating design concepts and developed a rule-based method [11]. Yan developed a co-evolutionary based method [9] and Jacquelyn developed a biological knowledge based method [19]. Besides the above methods, in [2] the author summarized 13 existing methods.

One of the common problems for both structured and computational methods is the evaluation of multiple design concepts. For a small number of design concepts, expert-based methods are feasible and effective. However, when we consider computational methods, a huge amount of design concepts would be generated, and the expert-based methods are infeasible, as shown in Fig. 1. Therefore, there is an urgent demand for a computational evaluation method to make the first round filter. After a small number of design concepts are selected, the expert-based methods can be used to make further filter. Considering the fact that functions are the most important information of design concepts, this research triesto develop a function-based computational method for evaluating design concepts based on a huge number of granted patents. To implement this goal, we address two research questions.

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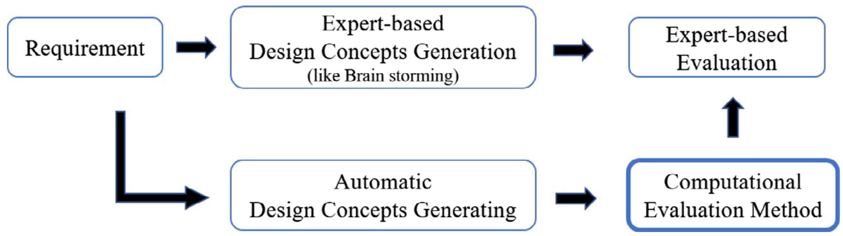

Fig. 1. An illustration of the requirement of computational evaluation method.

1. First, whether it is possible to define computational metrics for measuring design concepts.
2. Second, whether it is effective to use the computational metrics for measuring design concepts.

The rest of the paper is structured as follows. The next section provides some background for this study. The following section explains the proposed method in detail. Section 4 conducts six experiments for verifying the effectiveness of the computational metrics. Section 5 discusses the experimental results. Section 6 summarized this research and outlines some possible future studies.

2. Related works

Some researches have paved the way for this work, and in this section, we make a brief summarization of the research works. Three topics will be addressed, including concept representation, function vocabulary and design concept evaluation.

2.1. Design concept representation

Design concept representation is a critical foundation for computational design concept generation, since structuralization is the foundation of computation. The earliest structured representation of design concept was called function structure [22], which defines all functions and the relationships between functions, and the relationships are defined by flow (material, signal and energy). This kind of model can be constructed based on the function tree [32] and function-means tree [21]. Following this idea, several structured methods were developed, including Function-Behavior-Structure (FBS), Structure-Behavior-Function (SBF) and Function-Behavior-State. These methods only define the structure while ignore the vocabulary, which means the terms of functions are not restricted by a standard vocabulary. With the development of standard vocabulary (like FB and RFB in Section 2.2), Kurtoglu proposed a new structured method for representing design concepts, which is called "Configuration Flow Graph (CFG)" [10]. This method provides both structure representation and standard vocabulary for defining functions and their relationships as well as components for implementing functions.

From the above, we can see that functions are the most important information of composing design concepts. Therefore, it's reasonable to evaluate a design concepts based on the functions of composing the design concept.

2.2. Function vocabulary

This work studies the computational evaluation metrics at the function level. Therefore, function vocabulary is important. In 1984, Pahl constructed a function vocabulary at a very high abstraction level, which includes only five functions (transit, connect, deform, convert and store) and three flows (material, signal and energy)[22]. Following this offshoot, Hundal defined six top-level functions (branch, transit, connect, deform, convert and store) with some detailed definition of sub-functions, and the total number of functions is 44 [7].

In the recent years, Robert and his team built a vocabulary called "Function Basis (FB)" [30], which is extended from Little's work [14]. FB includes eight top-level functions with 24 sub-level functions. Based on FB, Julie integrated it with NIST (National Institute of Standards and Technology)[31] and formulated a new vocabulary called "Reconciled FB (RFB)" [3], which includes 8 top-level functions with 22 sub-level functions. In FB and RFB, the functions are defined one-by-one by human experts. Different with this, Murphy [18] constructed a vocabulary from 65,000 randomly selected patents, and this vocabulary includes about 1700 functions. Since our work is also based on a huge number of granted patents, this vocabulary will be adopted in this research.

2.3. Design concept evaluation

2.3.1. Evaluation metrics

The evaluation of design concept can be divided into process based method and outcome based method [28]. Process based method is to analyze and evaluate the whole cognitive process of generating design concept [12], which faces the difficulty that the inner mechanism of the cognitive process is unobservable. The outcome based method is more feasible than the process based method, and it's a prevalent way of design concept evaluation. The metrics are very important for evaluate design concepts.

In 2003, Shan proposed four metrics, including novelty, variety, quality and quantity [28,27]. Novelty means the degree of a given design concept is unusual with others. Variety means the degree of dissimilarity of a group of design concepts. Quality means the degree of a given design concept is feasible. Quantity means the total number of a group of design concepts. During the last decade, the four metrics were acknowledged by the research community, although different terminologies were used by different authors. For example, in [19], the authors used "usefulness", which is similar to feasibility. In [36], the author used "originality", which is similar to novelty. In some researches, the term "diversity" is also used to denote variety. The four metrics were also extended. For example, Brent introduced a new metric by combining novelty and variety [20]. In [12], Kurtoglu developed a new metric named "completeness", which defines how well a design concept satisfies the required functions. In all, we can conclude that novelty, variety, quality and quantity are four basic metrics for evaluating design concepts. To keep consistency, this work will use novelty, diversity, feasibility and quantity as the terms to denote these metrics.

2.3.2. Evaluation methods

Design concept evaluation is a Multiple-criteria decision making (MCDM) problem [33], and many different methods from MCDM domain can be used [37,6]. Currently, the researches are focused on expert-based method [33], which adopts one or many experts to grade design concepts from one or more aspects. Based