Harnessing Multi-domain Knowledge for User-centric Product Conceptual Design

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Abstract: Conceptual design is the design phase that deploys product functions and structures based on user requirements and ultimately generates conceptual design solutions. The increasing diversification of products has led to the promotion of customized design that involves deep user participation. As a result, there has been a growing focus on user-centric conceptual design. In this regard, the relationship among users, designers, and design solutions has been subtly changed, which has brought challenges to the traditional designer-oriented design model. To address the complex understanding and decision-making problem caused by deeper user participation, emerging new user-centric product conceptual design models need to be discussed. In the new design model, addressing the changing or growing requirements of users through the design of solutions and leveraging multidisciplinary knowledge to guide the conceptual design process are the critical areas of focus. To further describe this design model, this paper examines the user-centric interconnection among users, designers, design solutions, and multi-domain knowledge. In order to optimize design solutions, the solution resolution process and knowledge mapping based on design deviations are considered effective approaches. In addition, the paper also presents the types of design deviations and the multi-domain knowledge support techniques.

1 Introduction

Concept design is the focus of modern design theory research, and it is responsible for the originality and uniqueness of products[1]. It is an early design process in which multiple human participants, such as users and designers, are involved in defining design tasks, formulating product functions and structures, and obtaining initial conceptual design solutions based on user requirements, and it can have profound effects on the design and manufacture of subsequent products[2]. The purpose of the conceptual design solution is to provide a basic design direction, describing the functional model of the product and the physical structure to achieve these functions[3]. Generally, the conceptual design solution of a product can be presented using design plan sketches, renderings and 3D models. Customized design and manufacturing as a product development paradigm aims to provide users with tailored products[4]. The development of customized design has led to deeper participation of users in design, especially in conceptual design, which is conducive to meeting the diverse requirements of users.

However, it is difficult to correctly understand user requirements and design the ideal product that users have in mind. Previously, there were also a number of classic design approaches, such as agile development, in order to quickly respond to the dynamically changing requirements of users. Agile development focuses more on a development process of rapid iteration and delivery, which emphasizes the principles of small teams, short cycles and continuous delivery in order to respond faster to customer requirements and market changes[5]. The expression of real user requirements is difficult to achieve at once and often needs to be guided and reinforced through a continuous process. This progressive requirement, with its ambiguity and variability, creates more complex understanding and decision problems between users, designers, and design solutions. Because changes in the relationships between the objects involved in design lead to uncertainty in understanding and solution design, this

uncertainty surrounds the entire product design process, and to overcome this uncertainty, it is necessary to put the user at the center of the design. The user-centric product conceptual design is changing the traditional design system, and it needs to be built on a new design model.

In the context of the development of customization and intelligent design, user-centric product conceptual design is the future trend. To better introduce this design model, this paper is organized as follows: Section 1 introduces the future trends of product conceptual design. Section 2 introduces the study of key technologies for product conceptual design. Section 3 introduces the new model of the user-centric product conceptual design and the relationship between users, designers, and design solutions from the design perspective. Section 4 introduces the solution resolution process of user-centric product conceptual design. Section 5 introduces the knowledge support for the user-centric conceptual design model. Section 6 is the conclusion of this paper and the outlook for the future.

2 Literature Review

Conceptual design is a process of transforming user requirements into conceptual design solutions through designers, and the current research of conceptual design is mainly carried out from the design model, requirements understanding, solution resolution, and knowledge support.

The product conceptual design model is oriented to conceptual design solution generation, which integrates relevant design information and design methods through a process-oriented approach to ultimately guide designers to complete the product conceptual design. To reduce the impact of conflicts on requirement-function-structure mapping, the author's team proposes a smart conflict resolution model using a multi-layer conceptual design knowledge graph (mKGCD), which aims to provide innovative opportunities for conceptual design solution resolution[6]. Lee C et al. proposed a new knowledge-centred innovation service design (KISD)

model, which achieves acceleration of customized innovation service design through three phases: domain requirement acquisition (DRA), knowledge-centric resolution generation (KRG), and custom design knowledge-reasoning (CDK) phases[7]. Sousa-Zomer T T et al. proposed a quality function deployment (QFD)-based design support method for product-service systems (PSS), using over fuzzy hierarchical analysis (FAHP) to rank stakeholder requirements and reduce process ambiguity and uncertainty through fuzzy set theory[8]. Qian H et al. proposed a triple helix structural model of the innovative product design process, which constructed a general paradigm of the design process from three perspectives: design participation object, design knowledge, and design process[9]. Under the previous design model, users can only partially participate in the design process, such as the initial user requirements analysis and solution evaluation stages. The previous design models were designer-oriented design models by which designers could efficiently and accurately achieve an understanding and analysis of user requirements and solution development. As users participate more deeply in the design process, their requirements will change dynamically with the design process, and such dynamic requirements change the original design goals resulting in less efficient design and the designers' need to design iteratively. The impact of users' dynamic requirements will involve the entire design process, and traditional design models cannot match user-centric design thinking.

Requirements understanding has always been the focus of research in conceptual design, and previous research has focused more on how to help designers understand user requirements more precisely. Considering product aesthetics and consumers' emotional requirements, the author team here proposes a user-driven conceptual design specification that combines functional reasoning and aesthetic information analysis[10]. Yang Q et al. proposed an ant colony optimization-based customer requirements acquisition system and requirements expression guide. Kang B et al. incorporated head-mounted augmented reality (AR) technology into

the product development process to achieve low-cost access to real user requirements[11]. To help designers understand user requirements, Jin J et al. proposed using big data methods to analyze requirements, followed by using Kalman filtering methods to predict user requirements trends and Bayesian methods to compare products[12]. Previous research has focused on how to help designers more accurately understand the real requirements of users and use them as the basis for product design. However, user requirements are expressed vaguely at the start, and even users themselves are not sure what they want. Users need to be stimulated by staged design solutions to express their requirements more precisely, which poses a challenge to traditional user requirements analysis methods.

Solution resolution is also a key study in conceptual design. The author's team has previously proposed a method for using functional decomposition and conflict resolution to support resilient conceptual design[13]. Mao J et al. proposed a contradiction resolution method for product concept design that combines deep learning with technological evolution patterns to illustrate the mechanism of contradiction transformation from the perspective of system evolution and to provide a systematic, model-based design approach[14]. Delgado-Maciel J et al. combined the Substance Field Analysis (SFA) method and System Dynamics (SD) to design a tool capable of solving inventive problems and modelling conflicts through a set of dynamic relationships[15]. These theories are proposed based on summarizing designers' thinking rules and behavioural habits. Although they point out the participants of design activities and deeply analyze the gap between design solutions and user requirements in the design process, how this gap is generated and how it affects design still needs further in-depth research.

Multi-domain knowledge is the fundamental driving force of design innovation, and many scholars have conducted research related to the organization and support of multi-domain knowledge in conceptual design to promote innovation in solutions. Sarica et al. extracted terms from a large number of patent texts extracted from the U.S. patent database by natural language

processing techniques and used word embedding algorithms for knowledge association to finally construct a technical semantic network (TechNet), which realized the association of basic concepts and semantics in multiple technical fields[16]. Shi F et al. developed a "WordNet" focusing on design and engineering associations by integrating text mining methods to build an unsupervised learning ontology network and developed a platform called B-Link[17]. Hu, H et al. proposed a knowledge-based information representation model and an approach for archiving conceptual design information to represent and archive aesthetic information in hierarchical relationships[18]. Siddharth L et al. extracted triples from patent databases and constructed a large, scalable engineering knowledge graph based on rules for syntactic and lexical properties of claims in patent documents[19]. Luo J et al. proposed an InnoGPS, which integrates an empirical network map of all technology domains based on the international patent classification[20]. Liu Q et al. extracted design information from a large amount of unstructured text and constructed a function-structure concept network (FSCN)[21]. The designers occupy an important position in concept design, and their knowledge and experience determine the results of the design. The convergence, integration, and utilization of knowledge resources from different domains are conducive to avoiding failed designs due to limitations in thinking. With the development of customized design, users are participating more deeply in design, and to further meet the requirements of different individuals and groups, the knowledge support of multi-domain knowledge resources cross-fertilization needs to face each participating object and each stage in the new design model and realize knowledge update in time with the design process.

3 A new model of the user-centric product conceptual design

The conceptual design process usually includes several processes such as requirements analysis, functional decomposition, staged solutions generation, solutions design, and

evaluation. In the previous design process, the main decision maker of the design are the designers, and the users can only participate in the design in a limited way. Although many user-oriented design methods existed in the past, such as the analysis of user requirements and satisfaction[22] and quantification of user preferences[23-24], these methods considered more the analysis of user requirements and the true expression of these requirements to the designers, and as the users increasingly participate deeply in the design, there are multiple communications, feedback, and understanding between users and designers, and user requirements are dynamic and growing, which brings challenges to the previous methods.

User requirements are ambiguous, dynamic, and incompletely expressed[25-26]. With the improvement of people's material living standards, the characteristics of user requirements are amplified, and the conceptual design solutions under the traditional design model will be increasingly unable to adapt to the challenges brought by the ambiguous and fast-changing dynamic requirements of users, which will lead to the product not meeting the real requirements of users. Therefore, in order to ensure that design solutions meet the dynamic requirements of users in the future, it is necessary to establish a method to standardize the design solutions and a criterion to measure user satisfaction with the design solutions. In addition, the user requirements need to be integrated into the design process to update the requirements and guide the design solutions towards meeting these requirements.

Design essentially entails a mapping from ‘what we want to achieve’ to ‘How we want to achieve it’. The mapping exemplifies the design decision-making perse. Previously users could only participate in the design process to a limited extent, and as the users deeply participate in the design process, the influencing factors in the design process gradually change. The main participants of user-centric product conceptual design are shown below and the relationship between users, designers, design solutions, and knowledge is illustrated in Figure 1.

- Users. The users put forward constraint requirements for the product, from the

formulation of requirements to the experience and evaluation of the product, the users' participation makes the evolution of the design solutions directional, and the user requirement is one of the key drivers of product innovation.

- Designer. The designers are the role of narrowing down the understanding errors brought by cognitive differences through the scientific method of qualitative and quantitative analysis, and finally concretizing the vague and abstract user requirements into design solutions.
- Design solutions. Design solutions are the solutions obtained by the designers through the solution resolution process with the assistance of their own or external design knowledge.
- Knowledge. Multi-domain knowledge helps broaden the design space and provides knowledge aids for different roles such as users and designers.

It should be emphasized that depending on the degree of customization, the product may reflect individual requirements or the requirements of a group of users while depending on the complexity of the product, it may be designed by a single designer or by multiple designers. User requirements are influenced by multiple factors, such as market and technology, and evolve under the influence of these factors[12,27].

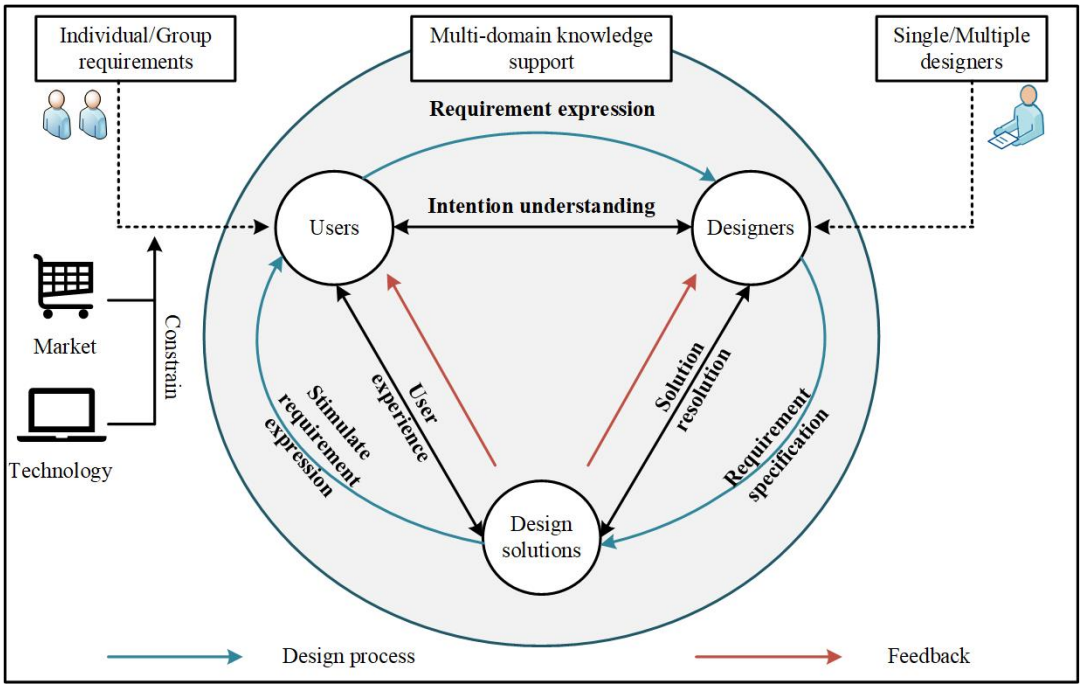

Figure 1 A model of the user-centric product conceptual design

In the design process, there is a mutual understanding process between users and designers, and the interaction between users and designers constitutes the core task of design, which is conducive to the clear expression of the design goal and the clarity of the design task. Through user experience, the design solutions can bring direct feelings and experiences to the users. Compared with the initial vague requirements, the users will be clearer about their requirements after experiencing the design solutions. In the process of user-centric product conceptual design, the user is one of the core participating objects of the design. The main roles that users play in the design are:

1) The role of the product experience. The users are the ultimate service object of the product, and the users are more concerned about the usability of the product. The essence of user experience is the user's understanding of the design solutions designed by the designers more concretely.

2) The role of generating requirements and interpreting requirements. User requirements are the starting point for designers to design products. User requirements are dynamic and as

the users experience the design solution, they may generate a clearer perception and expression of the requirements. Users can express their requirements even further through the experience. The generation and clearer expression of requirements is essentially an understanding of the users by the designers.

Designers take on the role of product creators and decision-makers in providing design solutions for the product, with a focus on realizing the product's function and structure. Knowledge serves the entire design process, it will facilitate the understanding between users and designers, assist designers in better solving design solutions, and at the user experience stage, it can help users to more accurately express their requirements. The user-centric product conceptual design process is a design process in which users are deeply participating. In this design model, the design solutions are not decided by the designers alone but are generated through multiple processes, such as further expression of user requirements, enhancement of the designers' understanding of the requirements, the re-establishment of the design task by the designers and the design of the solution again through the solution resolution process. The users, the designers, and the design solutions participate in the design together with the aid of knowledge.

4 Solution resolution process of the user-centric product conceptual design model

Due to the cognitive differences between users and designers, there exists a situation that the users cannot truly express their requirements and the designers cannot truly understand the users in the design process, which leads to inadequate solutions, and the design solutions need to go through several rounds to generate the satisfactory conceptual design solutions. The solution resolution process based on deviations is to link users, designers, and design solutions through three processes:

intention understanding, solution resolution, and user experience, and to ensure the expression of user real requirements and the products designed by designers truly meet users' expectations through multiple modifications of the solutions. It is important to emphasize that, unlike iterative design, user requirements change during the solution resolution process, and the solution resolution process is based on deviations in the process of spiral and continuous convergence to the latest requirements.

User-centric product conceptual design standardizes the design solutions through a continuous solution resolution process, which allows users and designers to participate in the whole design process, and ultimately leads to the convergence of design solutions with user requirements. The solution resolution process is shown in Figure 2. In this process, user requirements are complex and growing, and the design solutions are also evolving with the user requirements. The design solutions are designed based on the user requirements, and once the design solutions are obtained, the user experience stage of the solutions will follow. Usually, a one-time design does not result in fully satisfied users, so several solution resolution processes are needed to gradually improve the satisfaction of the product to the users. The user experience can determine the users' satisfaction with the design solutions, and then analyze the reasons for the dissatisfaction with design solutions. Through a continuous solution resolution process, design solutions can continuously converge with user requirements. This process can encourage users to express their requirements more effectively through the existing design solutions and help designers better understand the user's real requirements. Ultimately, this can ensure that the design solutions meet the user requirements.

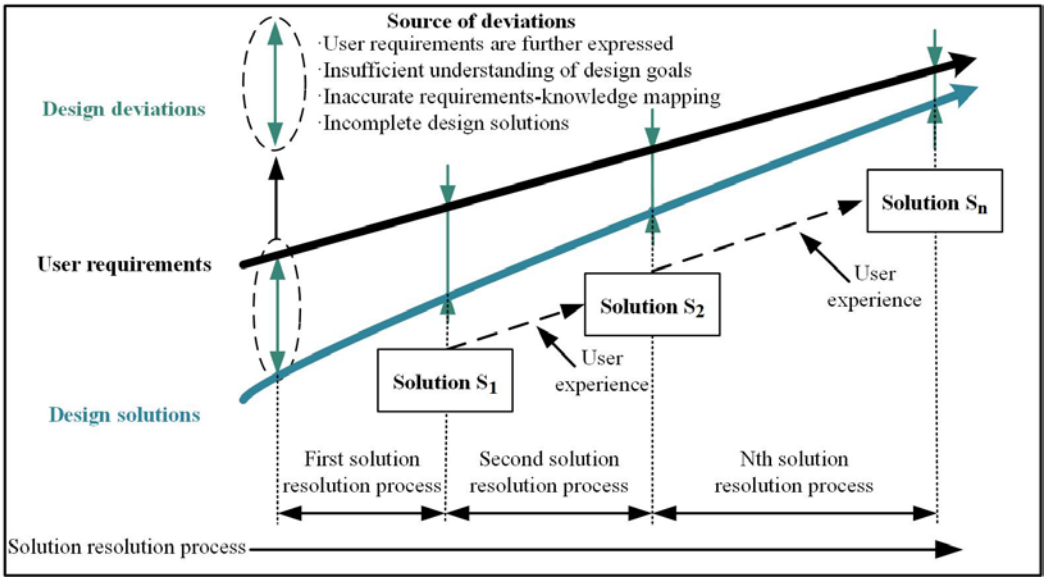

Figure 2 Solution resolution process of user-centric product conceptual design

The deviation is a measurement concept, which is a measure of the precision of the measurement result. Deviation in design is the gap between the existing solution and the ideal solution as perceived by the users. The deviation is the cause of the solution resolution process. The ultimate goal of design solutions is to meet user requirements, however, deviations are inevitable during the design process, which can lead to design solutions failing to meet user requirements. Because of the ambiguity, incompleteness, and dynamics of the user's expressed requirements, there may be understanding deviations in the intention understanding process. In the solution resolution process, there may also be solution deviations due to the limitations of different solution methods and the designer's design level. There are many sources of deviations, and the main reasons that can be identified for excessive deviations are mainly: user requirements are further expressed, insufficient understanding of design goals, inaccurate requirements-knowledge mapping, incomplete design solutions, etc. Five categories of situations in the design due to deviations are shown in Figure 3.

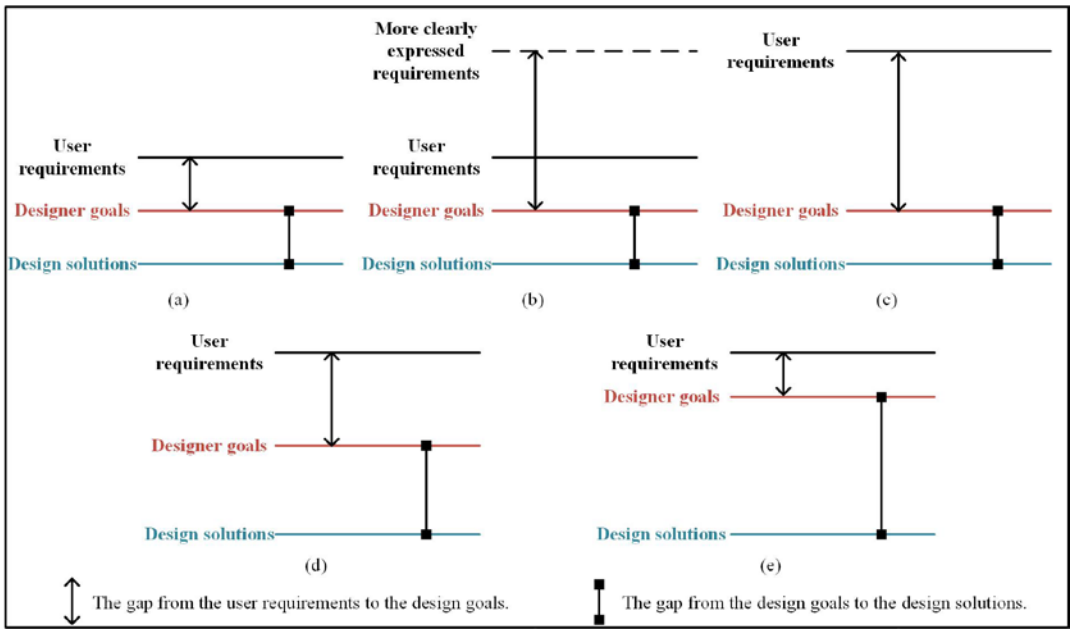

Figure 3 Five categories of situations in the design due to deviations

Category I. The design is reasonable. As shown in Figure 4(a) indicates that the design solutions are reasonable, and the designers have a clear understanding of the user requirements and design the solutions that make the users' experience favourable through the appropriate solution resolution methods, although there are still deviations at this point, the deviations are not significant.

Category Ⅱ. User requirements are further expressed. As shown in Figure 4 (b), the gap between the user's more clearly expressed requirements and the design goal is much larger than the gap from the user requirements to the design goal in Fig. (a). Although the designers get the staged design solutions through reasonable solution resolution, the design solutions at this time do not bring a good experience to the users, the users give a clearer expression of their requirements through the experience. At this time, the main reason for the excessive deviation is the further expression of user requirements.

Category Ⅲ. Insufficient understanding of design goals. As shown in Figure 4 (c), the gap between user requirements and design goals is much larger than the gap from user requirements to design goals in Figure (a). This indicates that the solution resolution is reasonable, but the main reason for the excessive deviation is the insufficient understanding of design goals.

Category Ⅳ. Inaccurate requirements-knowledge mapping. As shown in Figure 4 (d), the gap between user requirements and design goals and the gap between design goals and design solutions are both larger than those shown in Figure 4(a). The designers do not fully understand the user's requirements and do not get the solutions that meet the expectations through appropriate solution resolution methods. This is the worst situation among the reasons for excessive deviation.

Category Ⅴ. Incomplete design solutions. As shown in Figure 4 (e), the gap between the design goals and the design solutions is much larger than that shown in Figure 4(a). At this time the designers' understanding of user requirements is accurate, but the designers' solution resolution method when converting requirements into design solutions is not appropriate, which leads to the design solutions do not bring users a good user experience, and users are not satisfied with the solutions.

In the design process, deviations are often unavoidable, which requires users, designers, and design solutions to identify and solve problems through understanding and feedback during the design process.

5 Knowledge support for user-centric product conceptual design model

Knowledge is the bridge between design problems and design solutions, which helps to improve the level of product design and designers' innovative design ability[28]. Conceptual design, especially for complex products, involves the organization and utilization of interdisciplinary knowledge[2]. Knowledge helps to stimulate designers' inspiration and expand their design space[21]. The richness of knowledge can help designers to produce more innovative design solutions, which can lay a good foundation for the later detailed design[29]. To conceptualize more creative products that meet the requirements of users during the conceptual design phase, current

researchers have conducted research mainly from the perspective of knowledge organization. To meet the dynamic requirements of users, user-centric product conceptual design pays more attention to the organization and management of Multi-domain and continuous knowledge in the issue of knowledge organization. Multi-domain knowledge can synthesize multidisciplinary knowledge to assist designers in generating multiple creative design solutions. Continuous knowledge emphasizes the timely updating of knowledge and sustainable knowledge assistance for all aspects of the design process. Knowledge is the abstract expression of experience, and advanced knowledge organization and management need to consider how to integrate Artificial Intelligence (AI) tools for knowledge collection and processing. Secondly, knowledge is tacit, and the development of deep learning technology assists with the mining and organization of tacit knowledge. Finally, the application of knowledge needs to learn and simulate designers' thinking of using knowledge through big data analysis technology to achieve more efficient recommendations. Knowledge graph has become an important research direction in the era of artificial intelligence by their excellent knowledge mining, organizing and reasoning capabilities[30]. Benefiting from the efficient organization and association of knowledge, a knowledge graph can still guarantee the quality of information services in the face of large amounts of data, which provides the possibility of multi-domain and continuous knowledge organization in user-centric product conceptual design.

The new design model requires more powerful knowledge support for each participating object and each process in the new model. To better assist design, advanced knowledge support technologies represented by knowledge graphs have started to be applied to the conceptual design process[21,31]. However, there are still two problems with the in-depth application of new knowledge support to user-centric product conceptual design. First, conceptual design focuses on transforming user requirements into functions, then realizing the transformation from functions to structures, and finally generating design solutions. How to implement knowledge support in function-to-structure mapping to help designers avoid wrong designs due to changing user

requirements and unreasonable solution resolution, which will help reduce designers' workload. Second, the design process is a joint participation of users and designers, how to provide effective knowledge support for the staged solutions, users and designers to ensure that the solution resolution process is spiral and gradually converging. To address these two challenges, knowledge-driven strategies that integrate knowledge support technologies into the conceptual design process are proposed, as shown in Figure 4.

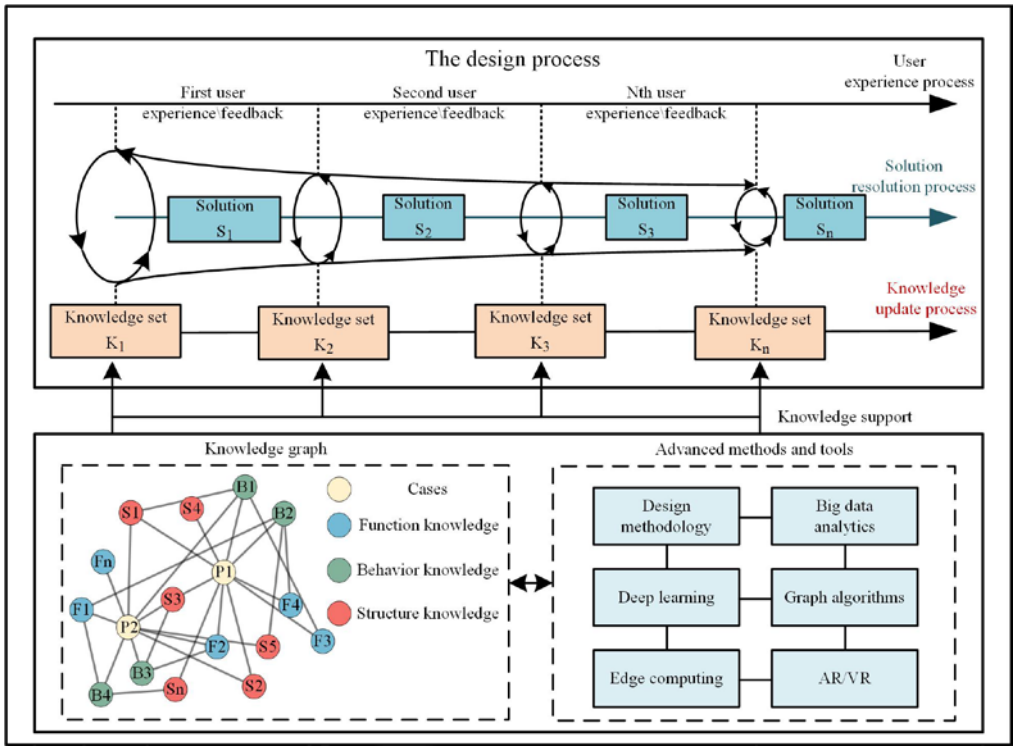

Figure 4 Knowledge-driven strategies for integrating knowledge graph into the conceptual design process

In this process, the solution resolution process, the user experience process, and the knowledge update process are three closely related processes. The true expression of user requirements in the design process and the correct resolution of the design solution are the core of designing a product that satisfies users. The advanced knowledge support technology provides a knowledge set for each stage of conceptual design solutions, which will help the expression of user requirements and assist the designer to resolve the design solution correctly. The knowledge set provides designers with function, behaviour, and structural knowledge related to the product to reduce designer workload

and improve design efficiency and is updated at the end of each design stage to prepare for the next round of revisions. As the design process progresses, the knowledge set becomes increasingly rich and precise, while user dissatisfaction with the product gradually diminishes, culminating in the finalization of the product design. Advanced knowledge support cannot be separated from the support of advanced technology, and more advanced methods and tools will further facilitate design intelligence in the future.

This paper points out that user-centric product conceptual design is the focus of the next generation of conceptual design. The content of this paper is based on the authors' thinking about user-centric product conceptual design but still has some limitations. First, it remains a challenge to further reduce the workload while designing the product that best satisfies the user. A calculation method that includes deviation value and its rate of change needs to be further investigated. Secondly, how to obtain the real requirements of users completely and comprehensively at one time is the key technology that needs to be overcome for mass customization product technology, and AI tools for deep user requirements mining can assist designers to understand user requirements more truly.

Currently, there are still some challenges and opportunities for conceptual design. Knowledge-driven user-centric product conceptual design facilitates better meeting the dynamic requirements of the user in the context of the customization and intelligence era. In the future, continuous iteration of design solutions needs to be considered in the context of sustainability and multi-domain knowledge assistance. Therefore, this paper makes the following outlook on the future development trend of conceptual design. (1) The development of technologies such as deep learning, edge computing and data mining has driven the development of AI-based tools, which are beneficial in assisting users to express their real requirements, as well as in facilitating designers to analyze and understand users further. At the same time, AI tools provide favourable assistance for design knowledge acquisition, organization and management, which will greatly improve design efficiency. (2) Constructing relevant functional and structural knowledge bases for different types of products,

especially complex products, to realize the organization and association of design knowledge among different products. Further enriching knowledge resources will help broaden the design space of the designer, and the organization and reuse of knowledge will be more conducive to the design of more creative and complex products. 3) Transform the inherent design thinking of designers to make them accept the user-centric product design concept.

6 Conclusion

With the promotion of customized design, deeper user participation in design has brought about more complex understanding and decision-making problems, posing challenges to conceptual design in the field of design. This paper focuses on several key topics in the new design model, 1) the relationship between factors that influence user-centric product conceptual design. 2) an adaptation of design solutions to dynamic requirements. 3) the organization and support of multidisciplinary and continuous knowledge. The continuous solution resolution process was proposed in this paper as a way to achieve continuous convergence of the design solutions toward the user requirements, which facilitates the clarity of design goals during the design process, and deviation is the cause of the continuous solution resolution process. The content of this paper is based on the authors' thinking about user-centric product conceptual design but still has some limitations. It remains a challenge to further reduce the workload while designing the product that best satisfies the user. A calculation method that includes deviation value and its rate of change needs to be further investigated; How to obtain the real requirements of users completely and comprehensively at one time is the key technology that needs to be overcome for mass customization product technology, and AI tools for deep user requirements mining can assist designers to understand user requirements more truly.

The development of intelligent technology will promote the existing design methods toward a

more intelligent and user-centric trend. In the future, the continuous resolution of design solutions needs to be considered in the context of sustainability and multi-domain knowledge assistance. Therefore, this paper makes the following outlook on the future development trend of conceptual design. (1) The development of technologies such as deep learning, edge computing and data mining has driven the development of AI-based tools, which are beneficial in assisting users to express their real requirements, as well as in facilitating designers to analyze and understand users further. (2) Constructing relevant functional and structural knowledge bases for different types of products, especially complex products, to realize the organization and association of design knowledge among different products will facilitate the innovation of solutions. (3) Transform the inherent design thinking of designers to make them accept the user-centric product design concept.

Acknowledgement

This research was partially supported by the National Natural Science Foundation of China (52175241) and two projects from the Sichuan Science and Technology Programme (2022ZDZX0040, and 2023YFG0058).

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