Modeling of the Human Cognition for the Metaverse-Oriented Design System Development

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Abstract. Metaverse can fully satisfy users' design scenarios, meeting their emotional and functional imaginations without any physical constraints, and its superior functionality makes it particularly suitable for the design domain. However, because the interactivity that the Metaverse can provide has not been fully exploited, its application in the design domain has not been studied. In this paper, we propose an interactive design system for the metaverse to enhance human interaction with the metaverse and to realize the interconnection between digital and real spaces. The system is expected to integrate the physical content of the design (including product components) with the designer's expertise. To this end, we modeled the product design process and its associated design knowledge, which is key to realizing the system. The designer's expertise was extracted and modeled as multiple perceptual-cognitive models. A fuzzy transformer method was innovatively developed for the computational modeling of the perceptual cognitive models. Using these models, user-system interactions and interactions between virtual and real products were enhanced. This work provides a conceptual framework for a Metaverse interaction design system based on computational modeling of human perceptual cognition. The proposed system greatly extends the scope of Metaverse applications for the development of various product design systems.

Keywords: Metaverse Design System · Design support system · Knowledge-based system · Human-centred design · Fuzzy transformer

1 Introduction

Metaverse can provide users with a connection between the real world and the virtual world, bringing them an immersive experience [2], and it is considered to

R. Akerkar (Ed.): SAIDD 2023, CCIS 1810, pp. 65–79, 2024.
https://doi.org/10.1007/978-3-031-53770-7_5

be another revolution in the Internet [1]. Meta-world can be regarded as an extension of today's Internet with a digital representation. It is a three-dimensional virtual space in which users can interact through avatars [3]. Metaverse space and the avatars inside it create a network of virtual worlds [4] in which users can socialize, trade, and other activities [5]. Current metaverse worlds are more commonly found in the gaming and entertainment industry [1], but the value of metaverse to the design field is also immense.

In terms of design, Metaverse provides a new virtual environment [6]. Through the use of augmented reality and virtual reality technologies, users' design solutions can be better met in this environment, fulfilling their emotional and functional imaginations without any physical constraints. In other words, Metaverse provides designers with an imaginative space to generate creations with a wide range of possibilities, and it is particularly suitable for design. In this space, designers can imagine their emotional and functional design concepts and evaluate their design solutions in a digital environment. Whether it's for various scenarios such as dressing an avatar [7], giving a lecture [8], building a house [9], or hosting a concert [10], designers' imaginations can be put to great use. In fact, the image space provided by the Metaverse immersive interactive environment enhances the interaction between designers and users. This interaction enables systematic human-product-environment interaction, which greatly facilitates human-centered design. This interaction can be between the present and the future or between the real world and the virtual world. This interaction blends digital environments and sensory experiences, taking digital design to a whole new level.

However, the interactive nature of the Metaverse has not yet been fully realized and exploited. This is because the digital and real spaces are not yet fully connected. The digital environment of the metaverse should have integrity and be able to fully integrate the physical content of the design, i.e., the product components and the designer's expertise. Therefore, design systems that can connect digital and real spaces are crucial for human interaction with the metaverse. Currently, the prevalent design system research is from a technology-oriented perspective, starting from the technical aspects of design system development and focusing on the creation and application of innovative technologies such as methodologies and software prototypes [11].

Design is an advanced human activity [12]. Design practices are accomplished based on a universal design process and its associated design knowledge [12]. Knowledge is becoming increasingly important in the development of systems in the meta-universe [7]. The realization of these systems in the meta-universe is only possible if the design knowledge is fully and rationally utilized in the different design processes; therefore, these digital tools are limited. Their limitations are mainly reflected in the fact that (1) they can only provide basic technical support for the design process [14]; (2) they are developed individually for specific design phases; and (3) these digital tools cannot be used systematically in conjunction or integrated into the complete apparel design process because the design knowledge is not sufficiently extracted and applied to the design process.

In order to realize the proposed Metaverse interactive and personalized design system, different design knowledge and its associated design processes should be fully extracted and utilized as the basic computational models supporting the proposed design system. With these computational models, designers can fully utilize their expertise in their imaginary world (digital environment) and easily translate their design solutions into a real manufacturing environment. Subsequently, human-product interactions as well as real-digital interactions in the digital environment can be optimized, and Metaverse's application scenarios can be expanded. As a result, the Metaverse design system is more advanced than all previous design systems.

The proposed system follows the general design process of "design-demonstrate-evaluate-adapt". Different computational perceptual cognitive models will be developed to extract relevant knowledge to support this process. The main parts of this work are as follows:

- We developed a knowledge-based interactive design system for Metaverse to enhance the interaction between users and Metaverse. Different computational perceptual cognitive models are developed to support the proposed system, ensuring that the system is able to generate design entities that correspond to user requirements.
- A general design process of "design-display-evaluate-adjust" is proposed and applied to the proposed system to realize the interaction mechanism of the system.
- In terms of computational modeling of perceptual-cognitive models, a fuzzy transformer approach is innovatively developed. These models form the basic models for design-related knowledge modeling.

2 The Proposed System and Its Disciplinary

2.1 Principle of the Proposed System

The real-world environment, the Metaverse virtual environment, the proposed system, and its interconnections are all included in the proposed system's structure, which is depicted in Fig. 1. The suggested system ties the outside world and the Metaverse together. The "Generate-Display Evaluate-Adjust" cycle is the general operating principle. All interactions between the real world and the Metaverse virtual environment are made possible by this mechanism, including those between user systems and the Metaverse and those between virtual and real products. To support these interactions, there is a design knowledge base that experts have already defined. It is a knowledge repository for all kinds of design expertise. Different perceptual cognitive computational models represent these many sorts of design information. They simulate the connection between product elements and design perceptions.

A user from the real world will utilize his or her avatar from the Metaverse to engage with the system in a genuine design case utilizing the suggested system. The user must first input their design specifications into the system. The

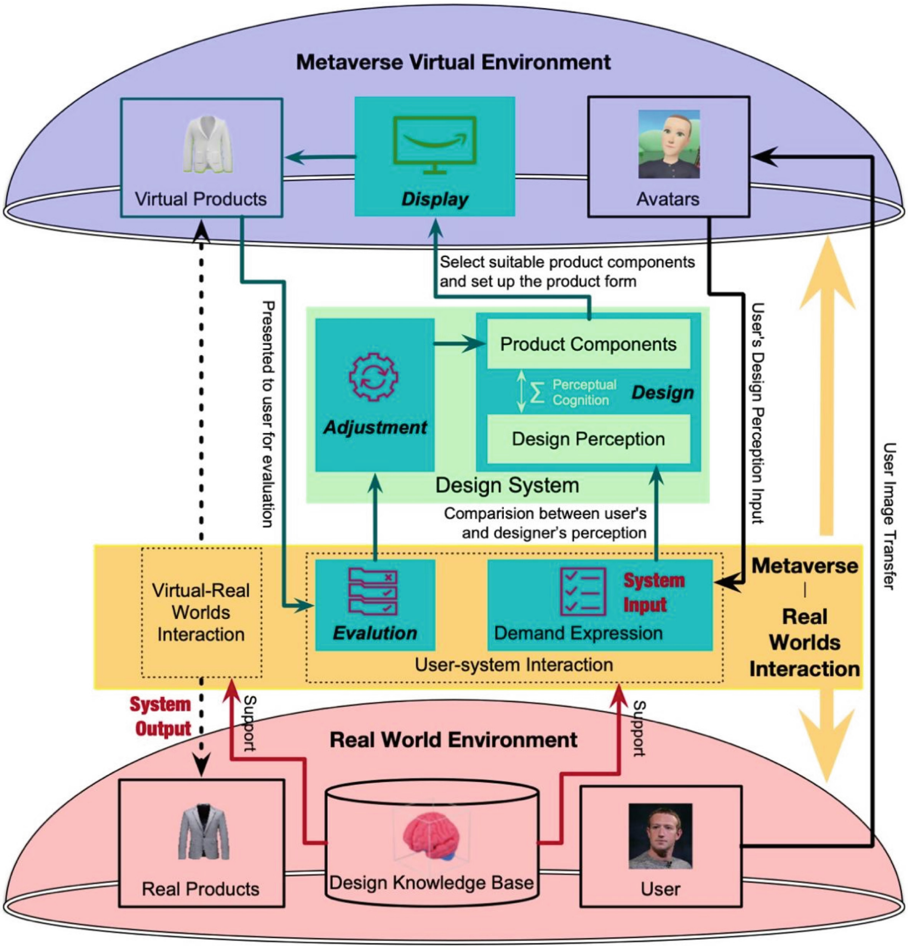


Fig. 1. Working flowchart of the proposed automatic pattern generation system.

design process will then become functional in the system. The user's design needs and the model's design perceptions of various product components will be compared using the perceptual cognitive computational model of the design knowledge base. The design outcome will be the pertinent product component with the highest design perception in relation to the consumer's requirement. The virtual product is then presented in Metaverse in a virtual form when the display software has been run. The user can indicate discontent with the generated design result because the assessment software is integrated within the system. The developed design result will be output and then produced in the real world if the evaluation result is satisfactory. The physical parameters of the suitable virtual product can be automatically developed and transferred to the smart factory in the actual world with the help of the provided design knowledge base. The product will be made swiftly and given to the customer. On the other hand, a method for adjustment will be carried out if the evaluation results are unfavorable. The user must recognize the problematic product elements.

The system will study customer dissatisfaction with the aid of the Design Knowledge Base before changing other product components. There will be new design outcomes produced. The Design Knowledge Base and the perceptual cognitive computing model will then be updated. A fresh set of customized product design results will be produced when the feedback is assessed by the model changing various knowledge base rules. Until suitable evaluation findings are guaranteed, this procedure is repeated.

2.2 Related Concepts and Methods

Design, Design Knowledge and Its Computational Modelling. Design is a brain activity focused on interaction that is predicated on that interaction [13]. Design demands, design perceptions, and their interactions are the fundamental phenomena that are primarily studied in relation to the phenomena and rules in the design process. The user's view of a design is called design demand, and it is typically semantically pre-pressurized, such as "modern style." Design perception is the result of a long history of design practice and is characterized as a "form-style" interaction that has a beneficial impact on the design process [15]. Form alludes to a product's tangible parts. For instance, in the design of clothing, the term "apparel form" refers to the strong physically functional elements that make up the garment's overall shape, such as the sleeve and collar shapes. Style (emotional expression of product components) is the subjective opinion of the designer regarding the aesthetics of the product components. For instance, style in the context of fashion refers to the appearance of a clothing detail. It has significant emotional characteristics and is articulated by generic semantics like "avant-garde style". Designers typically view "shoulder pad design" in this instance as being more avant-garde. Additionally, it may be said that although clothing style is a physical state, fashion style is a perceptual condition.

"Communicate-conceptualize-solve" is the fundamental design method. This design method is reflected in the "Generate-Display-Evaluate-Adjust" cyclic interactive structure utilized in this system. The designer will obtain the design requirements, or the user's perceptions, during the communication phase. The semantics of describing the user's perception will be understood by the designer. The designer will then work alone to complete the ideation stage. The designer will initially engage with this phase's design requirements and impressions mentally. To create a design solution, eliminate product forms with emotional semantics or user perception semantics that are similar. For each category of product component, there are several potential choices during the actual design process. Consider the term "sleeve type" in the context of fashion; examples include "lamb's leg sleeve," "shoulder insertion sleeve," and others. Sleeve type is a component of garment style. As a result, to create the final design solution, the designer will choose the product components in each category with the highest degree of matching.

It can be said that the "form-style" relationship forms the cornerstone of how design needs and design perceptions interact. Until a final, satisfactory design is generated, this process typically takes several rounds of engagement. This makes the perceptual perception application scenario very interactive and provides easy access to feedback. When considering the processes of its use, this aspect needs to be thoroughly taken into account.

Design Perception and Its Descriptive Space. A Perception-Cognition Description Space (PCDS) must be constructed in order to ascertain user and designer perspectives. It can be used to represent both the user's design needs (user requirements) and the product's design perception (style). Adjectives often signify the scale of expression that conveys the perception of something according to the kanji principle. So, a set of paired adjectives make up the proposed Perception-Cognition Description Space (PCDS). The kind and quantity of adjectives used are essential for ensuring the accuracy of the perception/need portrayal.

Assuming that the Perceptual-Cognitive Descriptive Space (PCDS) is defined as S with l dimensions in a left-right comparison format, and taking fashion as an example, the space can be expressed as:

$$S = \{SP_1, SP_2, ...SP_{l-1}, SP_l\} = \{\text{“}simple\text{-}complex\text{”}, \text{“}formal\text{-}casual\text{”} ... \text{“}classical\text{-}modern\text{”}\}.$$

In this research, we define F_c as a 7-segment semantic evaluation set denoted as:

$$\{F_1, F_2, F_3, F_4, F_5, F_6, F_7\}.$$

It can be used to organize the l dimensions into a perceptual evaluation table. Take "simple-complex" using 7 segment criteria as an example, it can be identified as "extremely simple-very simple-relatively simple-moderate-relatively complex-very complex-extremely complex".

Product Components and Product Components Matrix (PCM). Ontology theory, which examines the generative and physical structure of products and their interrelationships, is the basic foundation for the study of product component matrix. It is determined utilizing techniques for morphological analysis. Products, product component categories, and product components are typically its three categories. They are set up in a tree-like form. The product component category and the relationship between its components, using fashion as an example, can be described as follows:

Product:

$X_1 = C_{1.1} = \{Product\}$

Product component category:

$X_2 = C_{2.1}, C_{2.2} .....C_{2.a} = \{structure, silhouette, color, ...\}$

Product components:
$X_3 = \{C_{3.1}, C_{3.2}.....C_{3.b}\} = \{C^1{}_{2.1}, C^2{}_{2.1}, ...C^q{}_{2.1}, C^1{}_{2.2}, C^2{}_{2.2}, ...C^n{}_{2.2}, ...C^n{}_{2.2}, ..., C^1{}_{2.a}, C^2{}_{2.a}, ...C^r{}_{2.a}\} = \{loosestructure, tight\ structure, ..., Casual\ structure, H\ type, Ttype, ..., A\text{-}type, ..., drop\ shoulder, ..., plunging\ sleeves\}$,
where $b=q+n+...+r$.

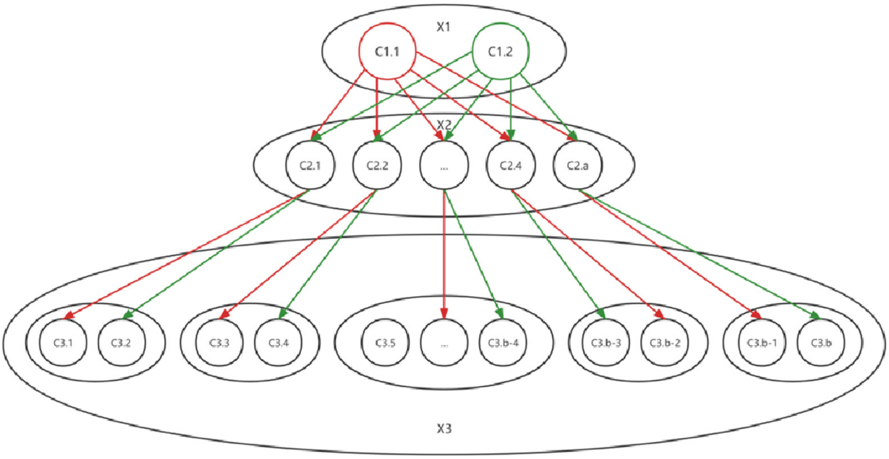


Fig. 2. The relationship between product, product component category, product components, and product family structure.

As is shown in Fig. 2, the hierarchical relationship of X_1, X_2, and X_3 reflects the product family structure of a certain product. The specific product X1 of the product is formed by combining the product component X_3 under each product component category of X_2. According to such affiliation and the mapping, the relationship network of the product family is formed. Figure 4 lists the product family structure of two products ($C_{1.1}$ and $C_{1.2}$). The actual product family relationship network is more complex and extensive than the figure.

Establishment of the "form-Style" Semantic Model Using Fuzzy Cognitive Map. Every component of the product has a corresponding perceptual picture expression. For instance, the "Bump Collar" reflects the "Formal Style" while the "Chest Patch Pocket" represents the "Casual Style" in terms of clothing style. The coordinate relationship between product components in the Perceptual-Cognitive Descriptive Space (PCDS) expresses the perceptual image of the Product Components Matrix (PCM). The fuzzy cognitive map can be used to replicate it, as seen in Fig. 3. It is possible to mimic as a semantic model the relationship between the product's constituent parts and the Perceptual-Cognitive Descriptive Space (PCDS) using the fuzzy cognitive map. A team of designers can execute this technique. The designer's expertise can be fully extracted using this approach.

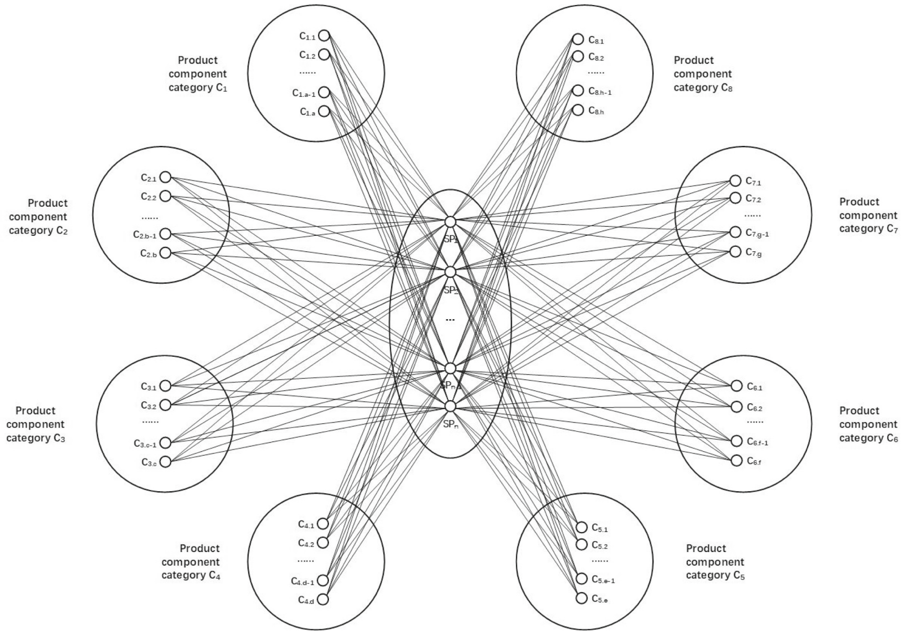


Fig. 3. An example of the fuzzy cognitive map of the "form-style" relationship.

Quantification of the "form-Style" Semantic Model Using a Fuzzy Transformer Method. It is required to quantify the "form-style" link and then model it because the data gathered for this study are semantic assessment data. As seen in Fig. 4, we suggest a fuzzy transformer strategy to achieve this goal. First, fuzzy logic is utilized to quantify the findings of the subjective judgment as a traditional way for fuzzy modeling. A mean-based transformer approach is suggested to process the quantified data in order to cluster the data and produce the desired outcomes.

For example, using the pair "*simple-complex*", the perceptual scale is $\{extremelysimple\text{-}very\,simple\text{-}relativelysimple\text{-}moderate\text{-}relativelycom - plex\text{-}verycomplex\text{-}extremelycomplex\}$, and the evaluation semantics can be quantified by the triangular fuzzy numbers (TFNs) $\{(0,0,1),(0,1,3),(1,3,5),(3,5,7),(5,7,9),(7,9,10),(9,10,10)\}$. Corresponding to the set of semantic evaluation results $\{F_1,F_2,F_3,F_4,F_5,F_6,F_7\}$, it can be symbolized as $TFN(Fc)(c = 1,2,3...,7)$, $i.e., TFN(F1) = (0,0,1), TFN(F2) = (0,1,3),...,$ $TFN(F7) = (9,10,10)$ respectively.

$TFN(Fc)(c{=}1,2,3...,7)$ are denoted as $TFN(Fc1), TFN(Fc2)$, and $TFN(Fc3)$ for the lower, maximum possible, and upper limits, respectively, i.e., $TFN(Fc1){=}0, TFN(Fc2){=}0$, and $TFN(Fc3){=}1$ for $TFN(F1){=}(0,0,1)$. Then, a number of fashion industry professionals are requested to conduct private, in-depth interviews. They are asked to assess findings pertaining to l dimensions of the Perceptual-Cognitive Descriptive Space (PCDS) in relation to b product

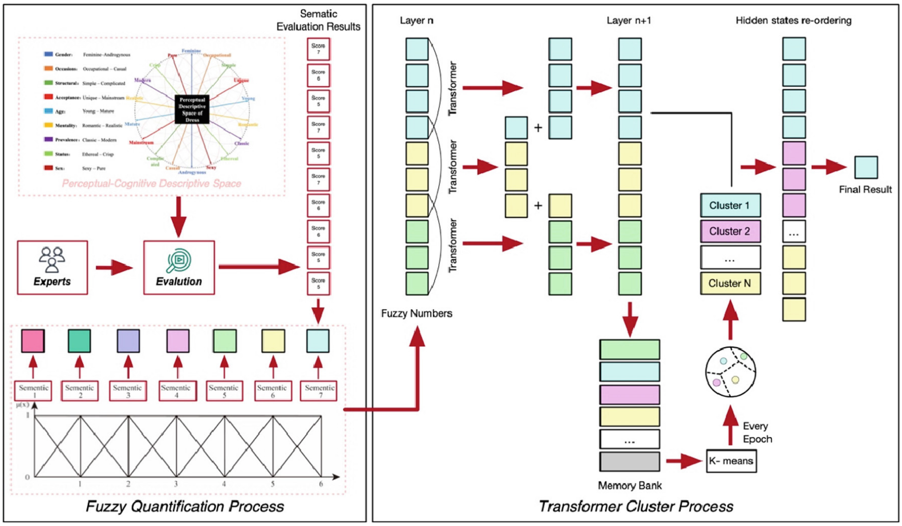


Fig. 4. The working principle of the proposed Fuzzy Transformer method.

components of the Product Components Matrix (PCM). Fuzzy logic will first be used to qualify all of the evaluation data for the data process. After clustering the data using the k-means-based transformer technique, the centroids of each product component are then determined on the various dimensions of the proposed Perceptual-Cognitive Descriptive Space (PCDS). After that, the quantified "form-style" model is acquired. This method outperforms existing ones when it comes to "form-style" semantic modelling.

3 Case Study and Related Experiments

Clothing style is a significant representative of product design due to its complicated fashion trend, rich form, and powerful personalisation. Clothing style design requires specific design expertise as well as a thorough design process. Clothing style design's cognitive mechanism is a significant representative object in the research on perceptual cognitive mechanism. In order to illustrate the concept of the proposed system, this study uses the perceived cognitive mechanism of clothing as an example.

3.1 Experiment I: Computational Dress Perceptual Cognition Modelling

Experiment I aims to create a Dress Design Knowledge Base (DDKB), which describes the connections between all Dress Perceptual-Cognitive Descriptive Space (D-PCDS) dimensions and all additional Dress Components Matrix (DCM) components.

Experiment I consists of three steps : (1) the development of the Dress Components Matrix (DCM), (2) the establishment of the Dress Perceptual-Cognitive Descriptive Space (D-PCDS), and (3) the Computational modelling of the Dress Design Knowledge Base (DDKB).

105 panelists (experiment fashion designers) are used as the experiment's expert panel for this aim. To make sure that they had the necessary information for this experiment, all of the panelists were trained for 6 h per week for 2 weeks, covering topics including descriptive terms, fashion style perceptual words, dress component element categories, and dress components for each dress component category. The methods used for subjective evaluation and the experimental protocols were both well-researched.

Step (1): the development of the Dress Components Matrix (DCM)

- **Collection:** The 105 panelists that are involved must do a brainstorming exercise to come up with as many types of outfit components as they can. Each of them creates a list of categories for dress parts based on their individual design expertise, such as the silhouette, sleeve style, dress length, etc.
- **Screening:** All panelists are given the opportunity to screen all of the mentioned dress component categories. Following that, a "round table" debate is undertaken to decide which dress component categories are most appropriate. The screening is based on two ideas: (a) the essential component of the dress is decomposed into a number of independent and variable dress component categories, and each independent and variable dress component category should be selected to be complete and not repeated; (b) recombination of individual and variable essential dress component categories is able to result in a new dress form.
- **Selection:** All panelists are required to list variable dress components in various dress component categories. Create and pick the various dress components of each dress component category. The stated dress components are then chosen by all panelists after a screening procedure. Similar to that, screening is based on two ideas: (a) the essential components of the dress component categories are decomposed into a number of independent and variable dress components, and each independent and variable dress component should be selected to be complete and not repeated; (b) recombination of individual and variable dress components of each dress component category is able to result in a new dress form. The final Dress Components Matrix (DCM) is shown in Fig. 5.

Step (2): the establishment of the Dress Perceptual-Cognitive Descriptive Space (D-PCDS)

In this phase, an additional 100 female consumers between the ages of 16 and 45 were invited to join the panel in addition to the 105 panelists from the previous phase. The purpose of this step is to use questionnaires to pick the perceptual-cognitive descriptions of the various outfit components.

- **Collection:** The panelists were given instructions regarding the aim of the experiment, which was to as fully as possible list the descriptive terms used in defining the both the fashion-oriented as well as the emotion-oriented dress needs. Each trained panelist is expected to come up with a variety of categories based on his personal experience and knowledge of the perceptual-cognitive descriptive phrases used to describe apparel. In the end, 178 words were produced.
- **Screening:** The group of experts held a held a group discussion in order to eliminate overly-emotional words. The key idea for this screening was to eliminate dress perceptual-cognitive descriptive words with similar meaning. For example, ‘contracted’, or ‘reduced’. After that, all words were paired. The assessment team matched and reserved 69 pair of words
- **Adjusting:** 100 female consumers were provided the aforementioned pairings in exchange for questionnaires. Both paper-based and internet surveys were employed. These 100 ladies were required to choose at least 28 specified word pairings that they felt were pertinent. The designers then selected those word pairs that appeared more frequently than 60 percent of the time in those questionnaires. Finally, these 105 designers in the panel selected 9 of these couples. Thus, Dress Perceptual-Cognitive Descriptive Space (D-PCDS) establishment is finished (Fig. 5).

Step (3): the computational modelling of the Dress Design Knowledge Base (DDKB)
105 designer panelists are taking part in this step. To begin, each participant was instructed to subjectively assess each component of the Dress Components Matrix (DCM) in the Dress Perceptual-Cognitive Descriptive Space (D-PCDS). On a scale of 1 to 7, each panelist was asked to offer the best score they could, using the sensory evaluation technology as a guide. When evaluating the picture functions, a score of 1 would be provided for the least functionality, and a score of 7 would be given for the most functionality. Similar to how 1 would be the lowest value and 7 would be the greatest for the pair of perceptual words.

The computational relationship between the Dress Perceptual-Cognitive Descriptive Space (D-PCDS) and the Dress Components Matrix (DCM) is then constructed using the suggested fuzzy transformer approach, and the desired Dress Design Knowledge Base (DDKB) is developed (Fig. 5).

3.2 Exploring the Application of the Computational Dress Perceptual Cognition Model: Development of a Personalized Dress Design System

A customized dress design system can be created using the computational dress perceptual cognition model created in this study, as shown in Fig. 5. This system can perform the duties of a real designer because it is a “intelligent designer” system. The system is meant to intelligently create tailored clothing styles based on user needs.

The system operates on the “Design - Display - Evaluation - Adjustment” cycle as a general rule. The user will repeat the cycle until they receive a final outcome that they are happy with. The computational dress perceptual cognition model, which is part of the fashion design knowledge base, supports the proposed system's operation.

Customers will initially submit their design requirements based on the Dress Perceptual-Cognitive Descriptive Space (D-PCDS) when the system is operational. The information will be compared to the perceptual cognition data from the Dress Design Knowledge Base (DDKB)'s Dress Components Matrix (DCM). Then, the most comparable dress elements from each category will be chosen and arranged together as the final design. The user will then be able to assess the result when the system has presented it. The system will stop functioning if the user is satisfied with the solution. If the new user is not pleased with the design solution, he or she must specify which part of the clothing is bothering them. The system should be able to tell which category the unsatisfactory clothing component belongs to, then change another garment component in the order of decreasing resemblance. Up until a good outcome is attained, the "Design - Display - Evaluation - Adjustment" cycle will be repeatedly carried out. It is clear that the system is a dynamic, interactive system for individualized design. The proposed system may realize any interaction that might occur between actual designers and consumers. The system can be used as a DIY design system for customers to fully meet their unique needs or as a design assistance system to help designers with less experience produce accurate and efficient designs.

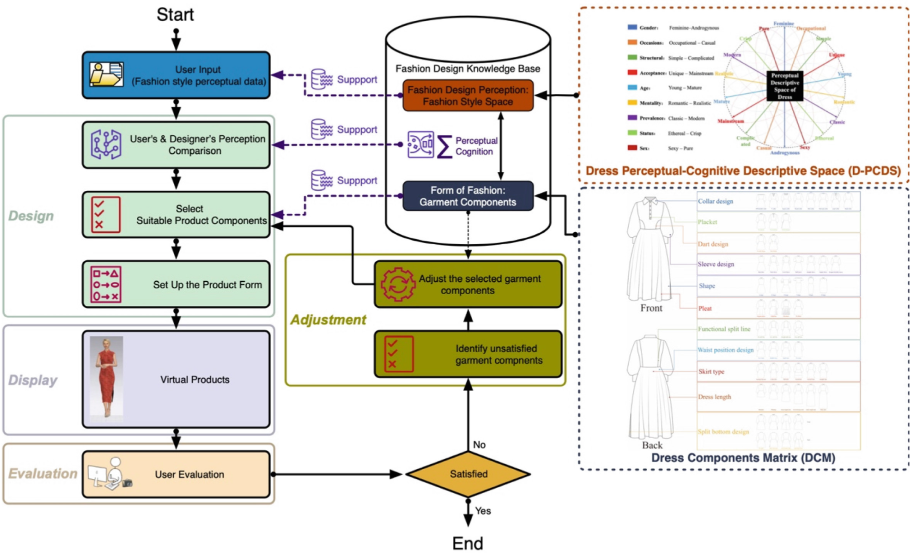
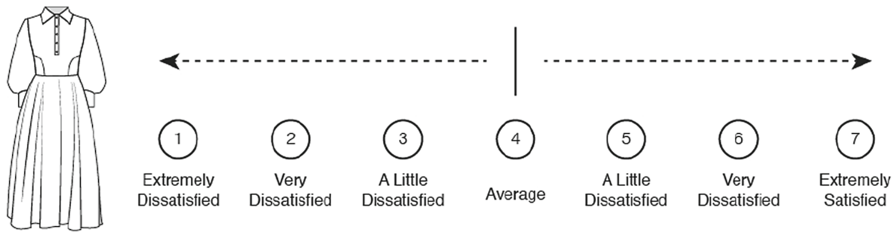


Fig. 5. Working flowchart of the proposed personalized garment style design system based on the proposed perceptual cognition computational model (CM-PCGSD).

3.3 System Evaluation

Using a group of 60 female users between the ages of 16 and 45, the results were examined to see if the proposed approach actually produces the desired results. Firstly They were all instructed to begin by evaluating the system-designed clothing subjectively. The dress pair of perceptual terms received the highest scores on a scale from 1 to 7, with 1 denoting "Extremely dissatisfied" and 7 denoting "Extremely satisfied," respectively. According to Fig. 6, the scores of 1 and 7 denote the highest and lowest levels of function for the evaluation of picture functions. The outcomes are displayed in Fig. 6. It is challenging to assess the reliability and stability of the 60 women who took part in this experiment because opinions regarding their satisfaction are considerably varying. So, to assess the data's stability, we utilized a variance test. The variation of the 60 involved users' satisfaction evaluation data, which covers 60 items, is 0.43, making it appear that the results are mostly steady. Based on this, we may conclude that the effectiveness of the experimental results has been verified.



User	Score	User	Score	User	Score	User	Score	User	Score
User 1	6	User 11	7	User 21	6	User 31	5	User 41	7
User 2	7	User 12	6	User 22	6	User 32	7	User 42	6
User 3	6	User 13	6	User 23	6	User 33	7	User 43	6
User 4	5	User 14	5	User 24	5	User 34	5	User 44	5
User 5	5	User 15	6	User 25	6	User 35	6	User 45	7
User 6	6	User 16	7	User 26	6	User 36	5	User 46	7
User 7	7	User 17	6	User 27	7	User 37	6	User 47	6
User 8	6	User 18	6	User 28	6	User 38	6	User 48	6
User 9	6	User 19	5	User 29	6	User 39	5	User 49	6
User 10	5	User 20	6	User 30	6	User 40	6	User 50	6

Fig. 6. A 7-point evaluation scale for dress design.

4 Conclusion

The goal of this effort is to broaden the use of the Metaverse to the realm of design. The development of an interactive knowledge-based design system for the Metaverse. The main difficulties in developing the system have been examined and overcome. The professional expertise of the designer is reproduced as a variety of computational perceptual cognition models. Ingeniously, a fuzzy transformer technique is created to assist this procedure. To support the system and ensure user-system-Metaverse interactions as well as virtual and physical product interactions, these models are kept in a design knowledge base. As a result, the proposed Metaverse design system's structural design has been abstracted from the general design process of Design-Display-Evaluation-Adjustment. The connection between the design knowledge base and the system can be realized using this procedure. It is also possible to improve user-system-Metaverse interactions. The effectiveness of the suggested system has been confirmed based on a genuine application scenario for using it in customized outfit creation. This paper offers a conceptual framework for the interactive Metaverse design system based on computer modeling of human perceptual cognition. The proposed system significantly broadens the Metaverse's scope of use and has a variety of product design system development applications. The connection between the system and the smart factory in the real world, as well as the modeling of product technical parameter modeling and its application to the proposed system, are future research directions.

Acknowledgments. This research was funded by the National Natural Science Foundation of China (Grant Number: 61906129), the China Association for Science and Technology Youth Support Talent Project (Grant Number: 2021-298), and the Hong Kong Polytechnic University GBA Startup Postdoc Programme 2022 (Grant Number: SP-22-13).

Author contributions. First Author and Second Author contribute equally to this work.

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