Design Studies and Intelligence Engineering
L.C. Jain et al. (Eds.)

doi:10.3233/FAIA231462

Research on Intelligent Shoe Washing Machine Design and Evaluation Method Based on AHP-DEMATEL

Feiyang LIU[a], Shuwei YU[a,1], Jiongzhou WENG[a], Jinwei LU[a], Ming ZHANG[a], Jinhong HU[a], Xiaojiang ZHOU[a]
[a] *College of Arts and Communication, China Jiliang University, Zhejiang, China*

Abstract. This study aims to improve user satisfaction in designing intelligent shoe washing machines using the AHP-DEMATEL method. Beginning with the collection and categorization of basic user data, AHP constructs a hierarchical analysis model of user requirements. DEMATEL is then integrated to identify and analyze comprehensive impact relationships among requirements. Weighted calculations determine the influence degrees between user demand data, resulting in composite factors based on AHP-DEMATEL. The intelligent shoe washing machine is designed based on composite user demand data, and outcomes are evaluated to establish a reliable product design scheme. Design, conducted using the AHP-DEMATEL composite method, is followed by satisfaction assessment using demand indicators, resulting in a completed scheme. Applying AHP-DEMATEL effectively addresses unclear user demand indicators during product development, significantly enhancing the user experience. This study provides valuable reference for similar product user demand research.

Keywords. Intelligent shoe washing machine, AHP, DEMATEL, evaluation method

1. Introduction

Shoe washing machines, as niche household appliances, have gained market recognition and experienced rapid demand growth this year, forming a potential market of billions. However, existing shoe washing machines are primarily modified versions of early washing machines, with working principles that do not align well with the needs of shoe cleaning, often resulting in shoe damage. Research shows that developers of shoe washing machines often underestimate the importance of acquiring user demand information and fail to properly process demand data, directly leading to products falling short of user expectations[1]. Therefore, reconsidering how to approach shoe washing machine product design, extracting and processing user demands in a scientifically rational manner, and evaluating the final design scheme are key factors in the success of development[2]. In response to these challenges, this paper proposes a research model for intelligent shoe washing machine design based on the AHP-DEMATEL method. It explores user preferences for attributes in intelligent shoe washing machine design,

[1] Corresponding Author: Shuwei YU, College of Arts and Communication, China Jiliang University, Zhejiang, China; E-mail: 553561524@qq.com.

gathers reliable user demand data, and ultimately creates a design scheme for evaluation, resulting in a user-satisfying product.

2. Current State and Significance of Shoe Washing Machine Design Research

2.1. Current State and Existing Problems

The shoe washing machine industry is undergoing a period of innovation and change, with the success of product design directly influencing marketability. Based on 2022 consumer data, shoe washing machine products are mainly categorized into semi-automatic and fully automatic types, utilizing internal brushes and friction to clean shoe surfaces. Some brands have added features such as air drying and drying to enhance the product experience. Considering industry development and product life cycle theory, these products are currently in the growth stage of their industry life cycle. The industry has not yet established standardized production specifications, and designs still adhere to washing machine principles and appearances, resulting in low cleaning efficiency, significant shoe damage, and inability to meet the demanding cleaning requirements of high-end branded shoes. Both industry development and user demand call for innovative solutions for such products. Several scholars have conducted research in this area. Wang Yinbin et al.[3] designed a shoe washing machine that uses ultrasonic waves for cleaning, reducing shoe damage to some extent but not resolving the efficiency issue. Xu Guanghong et al.[4] improved the entire shoe washing machine, designing a new type that combines cleaning, drying, and disinfection, achieving positive results. These examples indicate that while technological integration is a promising approach, deeper analysis of user demands is necessary for effective problem-solving.

2.2. Issues Addressed by the AHP-DEMATEL Method and Approach

The Analytic Hierarchy Process (AHP) is a scientific method that combines qualitative and quantitative analyses[5]. This approach breaks down factors related to the research object into multiple levels, calculating weights for each indicator to guide optimal method selection[6][7]. The Decision Making Trial and Evaluation Laboratory (DEMATEL) method is applicable to studying interrelationships among target factors. Its essence lies in utilizing graph theory and matrix tools to establish logical structural relationships among factors, identifying key elements within the system, and resolving complex problems[8].

In practice, many scholars have explored these methods, but individually, AHP and DEMATEL cannot fully address product design challenges. AHP overlooks cross-factor relationships, where one factor can be influenced by multiple higher-level indicators simultaneously, and it lacks clarity in analyzing interdependencies among factors at the same level. DEMATEL relies on expert rankings based solely on cause-and-effect relationships without considering factor weights or factors like user satisfaction as decision criteria. However, combining both methods effectively overcomes these limitations[9]. Initial indicator weights are determined using AHP, followed by DEMATEL adjustments to enhance accuracy and objectivity. This results in an evaluable design scheme. This paper primarily describes the AHP-DEMATEL combined method for product design and evaluation, using the intelligent shoe washing machine as a case study to formulate a design strategy.

3. Construction of User Demand Model for Intelligent Shoe Washing Machine Based on AHP-DEMATEL Method

The user demand model for intelligent shoe washing machines is constructed using the AHP-DEMATEL method. Initially, the AHP is employed to calculate the initial weights. of various indicators. Subsequently, the DEMATEL method is utilized to refine these weights, thereby effectively enhancing the accuracy and objectivity of weight assignments. During the process of deriving design solutions, the proposed design scheme is subjected to evaluation. Through comprehensive technological integration, the AHP-DEMATEL design and evaluation method is established. The specific method construction and workflow are depicted in **Figure 1**.

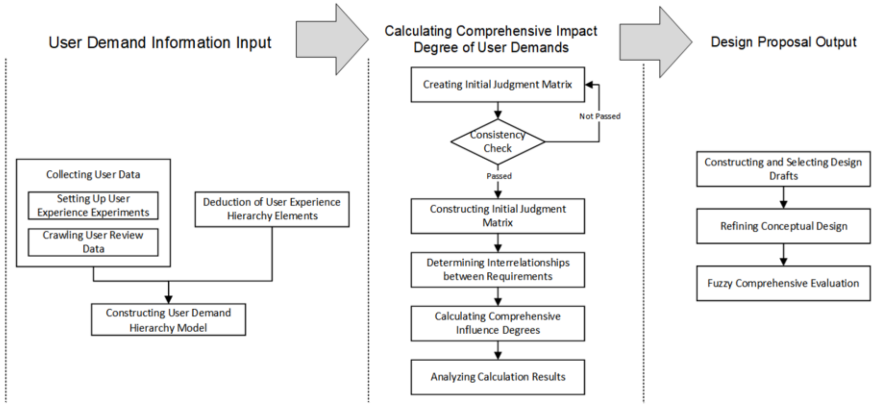

Figure 1. Design Process Flowchart Based on AHP-DEMATEL.

3.1. Constructing the Hierarchy Model of User Experience Requirements for Intelligent Shoe Washing Machine

3.1.1 Deriving User Experience Hierarchy Elements from Maslow's Theory

User experience spans the entire lifecycle of a product and is pivotal to realizing its commercial value[10]. Building upon Maslow's five levels of human needs, Luo Shijian [11]proposed five user experience requirements. Chen Wei[12] expanded upon this foundation by integrating the characteristics of industrial products and emphasized both material and spiritual attributes of products, resulting in six user experience hierarchy levels for design. Based on these levels of user experience design requirements and taking into consideration the user demands of intelligent shoe washing machine products, a re-analysis of these user experience elements and hierarchy levels can be conducted. These can be categorized into functional needs of practicality, intelligence, and efficiency; sensory needs of visual, tactile, and auditory experiences; emotional interaction needs of usability, communication, and preference; and self-needs of personalization and self-worth. This categorization effectively caters to diverse user demands, allowing for data extraction and analysis based on these hierarchy levels. The deduced relationships between user experience requirements are depicted in **Figure 2**.

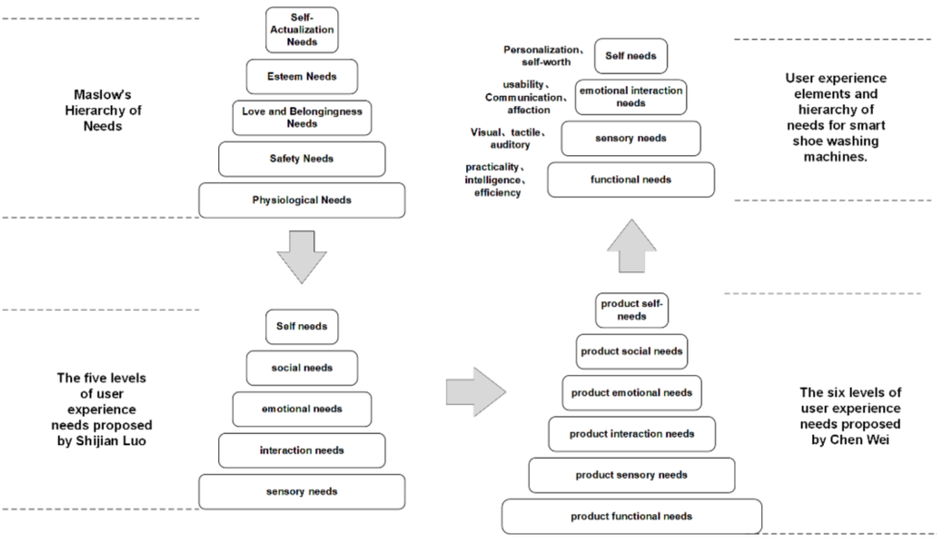

Figure 2. User Experience Requirement Hierarchy Diagram

3.1.2 User Demand Acquisition for Intelligent Shoe Washing Machine

Building upon the established user experience elements and hierarchy for the intelligent shoe washing machine, user experiments were conducted to assess the machine and collect feedback from ten university students. The experiment involved using everyday shoes, including canvas shoes, basketball shoes, and running shoes. Each pair of shoes was divided, with one allocated to the experimental group and the other to the control group. Participants followed the proper procedure for using the shoe washing machine to wash one shoe, two shoes, and four shoes simultaneously. Their actions were observed, and feedback was recorded, with consistent control variables such as washing program, duration, detergent type and quantity, and water temperature maintained throughout the experiments.

Following multiple rounds of experimental testing and the analysis of feedback from the ten participants, three main issues were identified:

1) Water Flow Impact: When cleaning a small number of shoes, the washing machine drum's size relative to the volume of shoes resulted in significant water flow interference, leading to insufficient contact with the brushes during cleaning. Conversely, cleaning four pairs of shoes at once led to crowding within the drum, resulting in suboptimal cleaning results.
2) Installation and Size Constraints: The use of the shoe washing machine necessitated the installation of water inflow and outflow pipes, restricting the experience to a fixed location. Furthermore, the machine's large size proved to be unsuitable for use in limited spaces.
3) Adhesive Separation Concerns: The shoe cleaning process, which takes 40 minutes, involves the shoes remaining submerged, making them susceptible to adhesive separation.

Based on the results of these user experience tests, it became evident that the tested shoe washing machine achieved a certain level of cleanliness but exhibited poor user experience, indicating the need for further optimization. Leveraging the feedback from these experiments, a web scraping technique was employed to search for and extract evaluation data related to shoe washing machines from e-commerce platforms such as JD and Taobao, using the keyword "洗鞋机" (shoe washing machine).This process yielded a dataset comprising 10,633 usable entries, which included usernames, evaluation content, and publication dates. After data preprocessing, involving the removal of duplicates and obviously illogical entries, an analysis and synthesis of word frequencies, user sentiment, and other factors within the evaluation content were carried out to identify user demands. By integrating the outcomes of the user experience tests and utilizing the user experience design hierarchy elements as an organizational framework, 20 key demand keywords were determined through additions, deletions, and further segmentation. This ultimately led to the creation of the Intelligent Shoe Washing Machine User Experience Demand Hierarchy Model, as illustrated in **Figure 3**.

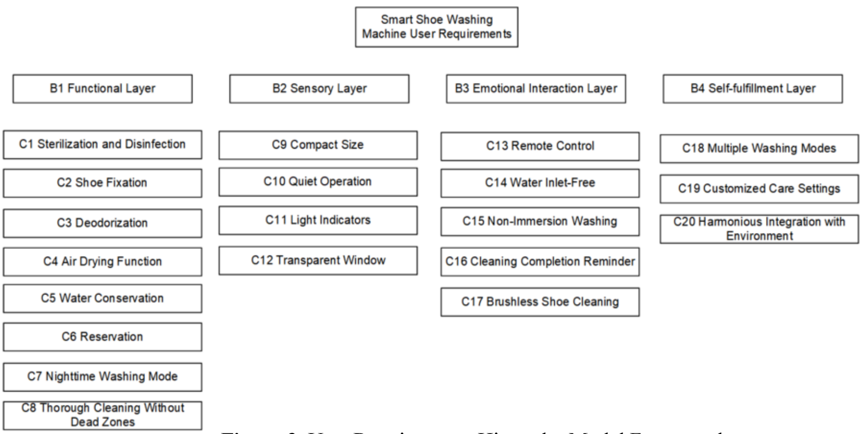

Figure 3. User Requirements Hierarchy Model Framework

3.2. Calculating Initial Weights and Consistency Check

3.2.1 Calculating Initial Weights

Based on the previously constructed hierarchy model for user experience requirements of the smart shoe washing machine, inviting a total of 30 participants, including expert users and regular users, to conduct pairwise comparisons for various factors using a 1-9 scale method, and establishing the initial judgment matrix Z. According to the fundamental principles of AHP , using a more precise geometric mean method to calculate the initial weight values W for the user experience requirements of the smart shoe washing machine, as shown in **Table 1**.

Table 1. Initial Weights of Intelligent Shoe Washing Machine User Demands

First-level Indicators / Second-level Indicators	B1 Functional Requirements	B2 Sensory Requirements	B3 Emotional Interaction Requirements	B4 Self-fulfillment Requirements	Initial Weight Values W
	0.344	0.211	0.248	0.198	
C1	0.083				0.029
C2	0.191				0.066
C3	0.102				0.035
C4	0.105				0.036
C5	0.193				0.066
C6	0.103				0.035
C7	0.122				0.042
C8	0.101				0.035
C9		0.236			0.050
C10		0.328			0.069
C11		0.175			0.037
C12		0.261			0.055
C13			0.156		0.039
C14			0.25		0.062
C15			0.271		0.067
C16			0.188		0.047
C17			0.135		0.033
C18				0.302	0.060
C19				0.336	0.067
C20				0.362	0.072

3.2.2 Consistency Test

To ensure the rationality of the Analytic Hierarchy Process, a consistency test should be conducted on the initial judgment matrix. The consistency ratio (CR) is used to measure the degree of consistency, and it is calculated using the formula: $CR = \frac{CI}{RI}$. Where CR is the consistency ratio, CI is the consistency index, and RI is the random consistency index. If CR is less than 0.1, it indicates that the initial judgment matrix is consistent; otherwise, the test fails, and the matrix needs to be adjusted. The values of CI and RI can be calculated using formulas $CI = \frac{\lambda_{max}-n}{n-1}$ and $\lambda_{max} = \sum_{i=1}^{n} \frac{(ZW)_i}{nW_i}$. Where λ_{max} is the maximum eigenvalue of the matrix and *n* is the number of criteria. Based on the formulas mentioned above, the consistency ratio CR for the judgment matrix composed of the first-level criteria is calculated to be 0.004, which is less than 0.1. Similarly, the CR values for the other judgment matrices are also less than 0.1, indicating onsistency.

3.3. Determining the Interrelationships of User Requirements for Smart Shoe Washing Machine

To assess the impact relationships between user requirements, an additional 30 expert users were invited to complete a DEMATEL questionnaire. They used a 0-4 scale to score a 16x16 matrix created from 16 specific requirements, thereby constructing the direct impact matrix *Y* for pairwise comparisons of requirements. The normalized direct impact matrix *N* was obtained using formulas $\boldsymbol{N} = \frac{\boldsymbol{Y}}{s}$ and $s = \max_{1\le i\le n} \sum_{j=1}^{n} y_{ij}$. The comprehensive impact matrix *T* was then calculated using formula $\boldsymbol{T} = \boldsymbol{N}(\boldsymbol{I}-\boldsymbol{N})^{-1}$. Where *I* is the identity matrix. Based on matrix *T*, the comprehensive impact relationships for each requirement were determined, including influence degree (D), being influenced degree (R), centrality (D+R), and reason degree (D-R), as defined in **Table 2.** Using these definitions, the comprehensive impact relationships for the smart shoe washer's requirements were calculated, and the results are presented in **Table 3**.

Table 2. Comprehensive Impact Relationship Definitions

Comprehensive Impact Relationship	Definition
Influence Degree (D)	The sum of each row in matrix *T*, indicating the overall influence of a specific factor on other factors.
Being Influenced Degree (R)	The sum of each column in matrix *T*, indicating the cumulative influence received by a specific factor from other factors.
Centrality (D+R)	Represents the magnitude of a specific factor's role within the system, with larger values indicating higher importance.
reason degree (D-R)	Reflects how a specific factor affects other factors. A positive value implies significant influence on other factors, classifying it as a causal factor. Conversely, a negative value suggests being heavily influenced by other factors, categorizing it as a result-oriented factor.

Table 3. Table of Comprehensive Impact Relationship for Smart Shoe Washing Machine Requirements

C_i	D	R	D+R	D-R	C_i	D	R	D+R	D-R
C1	0.638	1.566	2.204	-0.927	C11	0.276	1.558	1.833	-1.282
C2	1.918	0.75	2.669	1.168	C12	0.203	1.485	1.687	-1.282
C3	0.738	1.242	1.98	-0.504	C13	1.462	0.002	1.464	1.46
C4	1.591	0.988	2.579	0.602	C14	1.861	0.559	2.419	1.302
C5	0.132	1.138	1.27	-1.006	C15	0.935	1.765	2.7	-0.83
C6	1.892	0.821	2.713	1.071	C16	0.875	1.232	2.107	-0.357
C7	0.797	1.643	2.44	-0.846	C17	0.675	0.875	1.55	-0.2
C8	2.213	1.452	3.665	0.761	C18	1.632	1.063	2.695	0.569
C9	2.031	1.574	3.605	0.457	C19	0.681	0.558	1.239	0.122
C10	0.109	0.491	0.6	-0.381	C20	1.425	1.001	2.426	0.424

3.4. Calculating Comprehensive Impact Factor

Using a single method can lead to one-sided results in calculations, therefore it is necessary to weight the initial weights of each requirement with their centrality[13], constructing a comprehensive impact factor $X_i = W_i M_i / \sum_{j=1}^{n} W_j M_j$, as shown in **Table 4**.

Table 4. Comprehensive Impact Degree of Each Requirement

C_i	W_i	D+R	W_i*(D+R)	X_i	C_i	W_i	D+R	W_i*(D+R)	X_i
C1	0.029	2.204	0.064	0.030	C11	0.037	1.833	0.068	0.032
C2	0.066	2.669	0.176	0.082	C12	0.055	1.687	0.093	0.043
C3	0.035	1.980	0.069	0.032	C13	0.039	1.464	0.057	0.027
C4	0.036	2.579	0.093	0.043	C14	0.062	2.419	0.150	0.070
C5	0.066	1.270	0.084	0.039	C15	0.067	2.700	0.181	0.084
C6	0.035	2.713	0.095	0.044	C16	0.047	2.107	0.099	0.046
C7	0.042	2.440	0.102	0.048	C17	0.033	1.550	0.051	0.024
C8	0.035	3.665	0.128	0.060	C18	0.060	2.695	0.162	0.075
C9	0.050	3.605	0.180	0.084	C19	0.067	1.239	0.083	0.039
C10	0.069	0.600	0.041	0.019	C20	0.072	2.426	0.175	0.081

3.5. Analysis of Calculation Results

When comparing the rankings of comprehensive impact factors with the initial weights obtained solely through AHP, it becomes evident that the ranking based on comprehensive impact factors is more accurate. For instance, C9 although initially ranked lower when using AHP alone, holds a higher centrality ranking, indicating its significant influence on other factors. Given controlled costs and mature technology, it may be prudent to prioritize upgrading and iterating this element.

C5 initially assigned a higher weight, overlooked interrelationships among factors. After considering comprehensive impact relationships, this element is categorized as a result factor, influenced by other factors. Enhancing this function would require improvements to its source factors, potentially increasing development costs. Hence, practical development may require an adjustment of the development sequence accordingly.

Furthermore, C15 holds the highest ranking in terms of comprehensive impact factors, making it a top priority. Its centrality and causality also indicate that optimizing this factor can not only enhance product competitiveness but also significantly improve related factors. Addressing user feedback on suboptimal shoe cleaning effects by implementing C15 could lead to higher user satisfaction.

C10 initially had a relatively high weight and attractiveness, but its centrality is comparatively lower, considering it a result factor influenced by other factors. While it does impact user satisfaction and deserves attention, reducing noise falls under technical issues and faces challenges due to industry homogenization. Therefore, its development should be considered within the broader context of technical and cost considerations.

Based on the rankings of comprehensive impact factors, the top eight elements for prioritized implementation, considering development costs and technological capabilities, are C15, C9, C2, C20, C18, C14, C8, and C7.

4. Design Application of Smart Shoe Washing Machine Based on AHP-DEMATEL Method

4.1. Construction and Selection of Design Proposal Based on AHP-DEMATEL Method

Based on the aforementioned method, the weighted ranking results were obtained, and an AI-generated product concept map was created. Multiple user experience requirements were input as keywords into the Midjourney software, and after extensive. data training, three intelligent shoe washing machine design concepts were generated as shown in the **figure 4**. To achieve the most optimal design outcome and align with user requirements, a fuzzy comprehensive evaluation method was employed to assess the three design concepts. Ten experts are invited to use the primary indicators from the user experience requirement hierarchy as evaluation criteria, utilizing four levels of assessment: "Excellent," "Good," "Qualified," and "Unqualified." Scores above 90 are

Design Concept 1 Design Concept 2 Design Concept 3

Figure 4. Design Proposal

classified as "Excellent," scores between 80 and 90 as "Good," scores between 60 and 80 as "Qualified," and scores below 60 as "Unqualified." Through the calculation of the fuzzy evaluation results, Proposal 1 receives a score of 80.46, Proposal 2 scores 73.39, and Proposal 3 scores 74.87. Based on the results of the user requirement analysis, Proposal 1 is selected as the final design proposal for further development.

4.2. Design Solution Based on AHP-DEMATEL Method

Using the results of the comprehensive impact analysis, design solutions are developed. Visual representations of the effects can be seen in **Figures 5**.

1) Optimized Core Functions: The shoe washing compartment focuses on washing and drying, while the care compartment offers functions like sterilization, drying, and deodorization. The modular design ensures it's compact and lightweight, allowing users to customize combinations and configurations.
2) Improved Cleaning Method: Inside the shoe washing compartment, a stainless-steel frame holds shoes in place, and 35 high-pressure water jets clean the shoe surfaces from all angles, avoiding brush use that might harm the shoes. This fixation prevents prolonged soaking and related issues like adhesive separation. The compartment includes a 5-liter water tank for cleaning and wastewater collection, eliminating the need for hoses and improving the user experience.

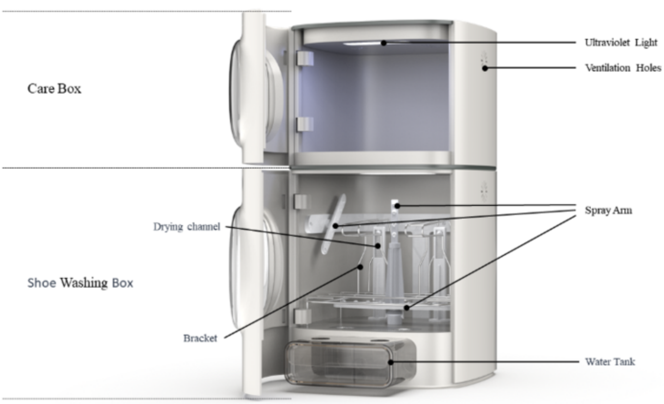

Figure 5. Functional Analysis Diagram of Smart Shoe Washing Machine

4.3. Design Proposal Evaluation Based on AHP-DEMATEL Method

To validate the feasibility of the design concepts, a comparison is made with three popular brands of shoe washing machines available on the Taobao platform, considering their sales volume and high ratings. Twenty expert users, including homemakers, design professionals, and frequent users of shoe washing machines, are invited to assess the four options using the fuzzy comprehensive evaluation method. The computed results are presented in **Table 5**.

Table 5. Comprehensive Scores of Four Shoe Washing Machines

product	Comprehensive Score
AHP-DEMATEL Smart Shoe Washing Machine	87.53
Changhong Fully Automatic Shoe Washing Machine	71.21
Audley Drum-Type Shoe Washing Machine	76.21
Midea Fully Automatic Shoe Washing Machine	74.33

5. Conclusion

This study focused on the intelligent shoe washing machine and employed a combined model that integrates AHP and DEMATEL to assess various factors comprehensively and establish a comprehensive ranking. The research findings highlight two key points. First, when compared to traditional design methods, the use of the AHP-DEMATEL approach effectively eliminates the influence of subjective factors in prioritizing product requirements. It also addresses the limitations stemming from the neglect of interrelationships between elements in the Analytic Hierarchy Process, enabling the accurate identification and resolution of design challenges to enhance user experience and product satisfaction. Second, applying this method to evaluate product proposals allows for the selection of more optimal design solutions, thus improving product suitability and enhancing the commercial value for businesses.

Acknowledgments

Project supported by the 2022 Zhejiang Province Curriculum Ideological and Political Project: Case Study of Ideological and Political Industrial Design Based on Correct Values, Project Number 113; The National Social Science Fund for Arts Project: Contemporary Paradigms and Standard Systems for the Inheritance of Chinese Traditional Crafts (20BG137).

References

[1] Yu, S., Lu, J., & Lu, T. Evaluation Method of Assembly Design for Electric Energy Metering Box Based on DFA Theory. Packaging Engineering **43** (2022), S1, 36-41.
[2] Geng, X., Xu, S., & Ye, C. Optimization Design of Product Functional Requirements Considering Quantitative KANO Analysis. Computer Integrated Manufacturing Systems **22** (2016), 07, 1645-1653.
[3] Wang, Y., Wang, Y., Ji, H., & Ding, Z. Design of a New Multifunctional Shoe Washing Machine Based on Ultrasonic Principle. Industry and Technology Forum, **17** (2018), 13, 53-54.
[4] Xu, G., Chen, B., Yang, L., & Zhang, Z. Development and Finite Element Analysis of a New Multifunctional Shoe Washing Machine. Machinery Design & Manufacture **10** (2016), 236-239.
[5] Deng, W., & Zhu, H. Design Evaluation of Children's Smart Watch Based on Analytic Hierarchy Process. Packaging Engineering **39** (2018), 8, 121-125.
[6] Xu, X., Liu, J., Yan, Y., & Yang, J. Development and Theoretical Trends of Intelligent Design Methods. Packaging Engineering **41** (2020), 4, 10-19.
[7] Hou, J., Zhang, Y., & Wu, L. Research on Design of Smart Baby Stroller Based on AHP Analytic Hierarchy Process. Packaging Engineering **43** (2022), 2, 50-55.

[8] Qin, X., & Lu, X. Research on Factors Affecting the Ecological Security System of Coastal Cities Based on BP-DEMATEL Model. Management Review **27** (2015), 5, 48-58.
[9] Zhang, H., & Ye, S. Research on the Mutual Relationship of Key Success Factors of PPP Projects Based on AHP-DEMATEL Method. Science and Technology Management Research **36** (2016), 22, 203-207.
[10] Luo, S., Zhu, S., & Ying, F. Context-Based User Experience Design in Mobile Interface. Computer Integrated Manufacturing Systems **16** (2010), 2, 239-248.
[11] Luo, S., & Zhu, S. User Experience and Product Innovation Design. Beijing: China Machine Press, 2010.
[12] Chen, W. Application of User Experience Design Elements in Product Design. Packaging Engineering **32** (2011), 10, 26-29+39.
[13] Liu, C., & Wu, Z. Study on Commercialization Factors of Renewable Energy Technology Based on AHP and DEMATEL. Science and Technology Management Research **35** (2015), 1, 107-112+116.