Research on Track Equipment Design Based on Product Family Theory

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Abstract. Objective: To enhance the intelligence and modularization of track equipment design, optimize the decision-making process, and improve the adaptability and scalability of product families. Method: The study integrates the AHP-QFD approach to analyze user demands and technical features, employs K-means clustering to categorize technical characteristics, and develops a genetic matching scheme for product family modules, including general, variable, and alternative modules. Based on this, a modular intelligent track inspection and maintenance equipment design scheme is proposed. Conclusion: The findings demonstrate that this method optimizes the modular configuration of track equipment, enhances universality, flexibility, and expandability, and exhibits superior performance in intelligent inspection, automated maintenance, and energy efficiency, thereby increasing market competitiveness. This research provides a systematic and efficient track equipment product family design approach, offering theoretical support and practical reference for the intelligent and standardized development of future rail transit equipment.

Keywords: Track Equipment Design; AHP; QFD; Product Family Theory; K-means Clustering

1 Introduction

China's railway industry has developed rapidly, serving as a key national infrastructure that facilitates travel while driving regional economic growth. Given the vast national territory and the increasing number of high-speed rail connections, ensuring passenger safety has made railway maintenance an increasingly significant concern.

As high-speed rail technology advances from structural and functional design towards operational safety assurance, maintaining a high level of track service regularity has become a critical scientific challenge[1]. Foreign countries initiated high-speed comprehensive inspection train development earlier, but their technologies have remained largely unchanged over the past two decades. While much research focuses on China's high-speed inspection trains, little attention is given to foreign counterparts[2]. Currently, various domestic track inspection, maintenance, and repair vehicles exist,

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but they lack systematic intelligence in design. Therefore, adopting suitable design strategies and processes to optimize track equipment is necessary.

2 Research Methods and Processes

2.1 AHP-QFD Model

Analytic Hierarchy Process (AHP), introduced by American operations researcher Professor Saaty in the 1970s, combines qualitative and quantitative analysis for systematic decision-making[3]. AHP's advantage lies in its hierarchical structure, allowing developers to understand the relative importance of user demands and construct hierarchical models to guide design practice.

Quality Function Deployment (QFD), proposed by Japanese scholars Akao Yoji and Mizuno Shigeru, systematically translates customer needs into design characteristics through a hierarchical analysis[4]. QFD maps multi-layered relationships between user needs and technical features, using a House of Quality (HOQ) to convert user demands into design parameters, thereby reducing development time and costs.

2.2 Product Family Theory

In biological terms, a "gene" is a DNA fragment responsible for hereditary traits. In industrial design, a "gene" refers to distinct product features that ensure brand identity and consistency across product generations[5]. Product family theory emphasizes not the design of individual products but the systematic relationship between products, aiding in brand establishment[6].

2.3 Design Research Process

AHP and QFD integration is widely used in design research. For example, Wang et al. applied AHP-QFD to elderly-friendly shoe-changing seats, integrating the Kano model for precise user demand identification[7]. Xiong et al. applied AHP-QFD to crawler-type mobile crushers, optimizing functionality and market adaptability[8]. Zheng et al. used QFD to extract user needs in medical bed innovation, applying AHP for weight determination to enhance design efficiency and user satisfaction[9]. Building on these approaches, this study integrates AHP-QFD for track equipment design, as illustrated in Figure 1.

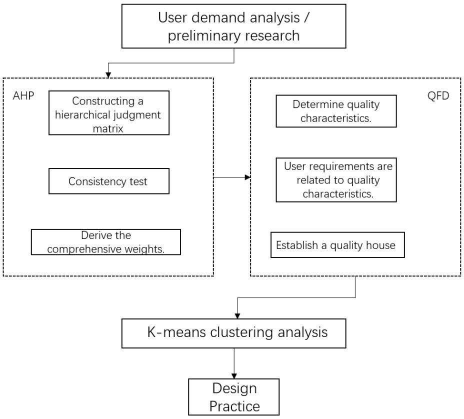

Fig. 1. Equipment Design Research Process

3 Track Equipment Demand Analysis

3.1 User Demand Hierarchy

User surveys and expert evaluations identified three primary demand categories for track equipment design: functional, aesthetic, and emotional. Functional demands include inspection, cleaning, maintenance, safety, and multi-task capabilities. Aesthetic demands cover modular appearance, brand identity, industrial aesthetics, and modernity. Emotional demands involve adaptability, environmental friendliness, and intelligence. The user demand hierarchy model is established, as shown in Figure 2.

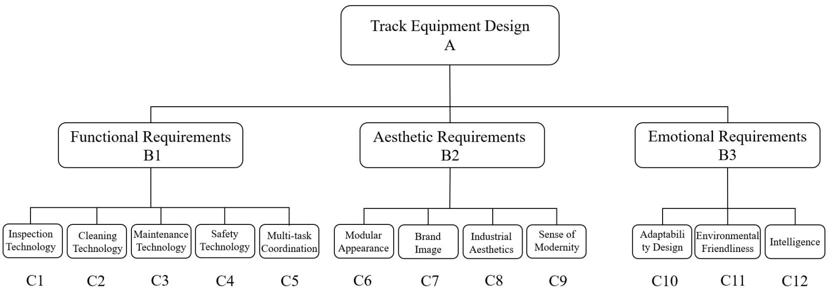

Fig. 2. Comprehensive Evaluation Index System for Track Equipment Design

3.2 Demand Weight Calculation

A judgment matrix was constructed to calculate weight values. After establishing a hierarchy model, pairwise comparisons were used to determine the importance of elements and their weights. Ten track equipment designers and ten design students were invited to construct judgment matrices using a nine-point scale and calculate the weights of 12 sub-elements. As shown in Table 1.

Table 1. Type Styles

Scale	Meaning
1	Two factors are equally important.
3	The first factor is slightly more important than the second factor.
5	The first factor is significantly more important than the second factor.
7	The first factor is strongly more important than the second factor.
9	The first factor is extremely more important than the second factor.
2, 4, 6, 8	Intermediate values between two adjacent judgments.
Reciprocal of the above values	When two factors are compared in reverse, the comparison value is the reciprocal of the original value.

3.3 Consistency Check of the Judgment Matrix

A consistency test ensures the logical accuracy of evaluations.

$$\mathrm{CI} = \frac{\lambda_{max} - n}{n-1} \quad (1)$$

The consistency index (CI) and consistency ratio (CR) were calculated.

$$\mathrm{CR} = \mathrm{CI}/\mathrm{RI} \quad (2)$$

If CR ≤ 0.1, the judgment matrix consistency is high and acceptable.

Table 2. Meets The Design Judgment Matrix For Rail Equipment

A	B1	B2	B3	W
B1	1	1.891	2.137	0.495
B2	0.529	1	1.751	0.304
B3	0.468	0.571	1	0.201

As shown in Table 2. Based on calculations, the maximum eigenvalue is 3.021, the weight of B1 is 0.495, the weight of B2 is 0.304, and the weight of B3 is 0.201, with a CR value of 0.021 which is less than 0.1, indicating that the consistency test has been passed.

Each criterion at level C evaluates the weight values of the indicators at level B, as shown in Tables 3 to 5.

Table 3. Judgment Matrix for Functional Requirements Criteria

B1	C1	C2	C3	C4	C5	W
C1	1	2.593	0.642	1.688	2.102	0.264
C2	0.386	1	0.404	0.796	0.895	0.119
C3	1.557	2.478	1	1.73	2.144	0.315
C4	0.593	1.256	0.578	1	1.898	0.179
C5	0.476	1.118	0.466	0.527	1	0.124

After calculation, the maximum eigenvalue is 5.052, the weight value of C1 is 0.264, the weight value of C2 is 0.119, the weight value of C3 is 0.315, the weight value of C4 is 0.179, and the weight value of C5 is 0.124, with the CR value being 0.012, which is less than 0.1, indicating that the consistency test has passed.

Table 4. Judgment Matrix for Aesthetic Requirements Criteria

B2	C6	C7	C8	C9	W
C6	1	1.954	2.242	1.685	0.421
C7	0.512	1	1.505	1.758	0.249
C8	0.446	0.664	1	1.358	0.184
C9	0.391	0.569	0.736	1	0.147

After calculations, the maximum characteristic root is 4.013, the weight value of C6 is 0.421, the weight value of C7 is 0.249, the weight value of C8 is 0.184, and the weight value of C9 is 0.147. The CR value is 0.005, which is less than 0.1, indicating that the consistency test has been passed.

Table 5. Judgment Matrix for Aesthetic Requirements Criteria

B3	C10	C11	C12	W
C10	1	0.888	0.754	0.289
C11	1.126	1	0.754	0.313
C12	1.326	1.326	1	0.398

After calculations, the largest eigenvalue is 3.002, the weight value of C10 is 0.289, the weight value of C11 is 0.313, and the weight value of C12 is 0.398, with the CR value being 0.002, which is less than 0.1, indicating that the consistency test has passed.

Finally, the weight values of all the demand elements in the criterion layer are multiplied by the corresponding indicator weight values in the indicator layer, resulting in the overall user demand weight value for the rail equipment, as shown in Table 6.

Table 6. Comprehensive Weight of Specific Requirements in Track Equipment Design

<table>
<tr><th>Criteria Layer</th><th>Criteria Layer Weight</th><th>Indicator Layer Weight</th><th>Comprehensive Weight</th></tr>
<tr><td>Inspection Technology C1</td><td>0.264</td><td rowspan="5">Functional Requirements B1=0.495</td><td>0.131</td></tr>
<tr><td>Cleaning Technology C2</td><td>0.119</td><td>0.059</td></tr>
<tr><td>Maintenance Technology C3</td><td>0.315</td><td>0.155</td></tr>
<tr><td>Safety Technology C4</td><td>0.179</td><td>0.089</td></tr>
<tr><td>Multi-task Coordination C5</td><td>0.124</td><td>0.061</td></tr>
<tr><td>Modular Appearance C6</td><td>0.421</td><td rowspan="4">Aesthetic Requirements B2=0.304</td><td>0.128</td></tr>
<tr><td>Brand Image C7</td><td>0.249</td><td>0.076</td></tr>
<tr><td>Industrial Aesthetics C8</td><td>0.184</td><td>0.056</td></tr>
<tr><td>Sense of Modernity C9</td><td>0.147</td><td>0.045</td></tr>
</table>

Adaptability Design C10	0.289	Emotional Requirements B3=0.201	0.058
Environmental Friendliness C11	0.313		0.063
Intelligence C12	0.398		0.080

4 QFD Transformation of User Needs

In the design of track equipment, the comprehensive weight of user needs in Table 6 is imported into the left wall of the House of Quality (HOQ). The track equipment requirements are then broken down into several technical characteristic indicators and imported into the HOQ ceiling. The values 0, 1, 3, and 5 are assigned to represent the correlation between user needs and track equipment quality characteristics as irrelevant, weak, medium, and strong, respectively, based on specific relationships.

$$W_j = \sum_{i=1}^{q} W_i P_{ij}\,, W_k = \frac{W_j}{\sum_{i=1}^{q} W_j} \quad (3)$$

Where:

- W_j represents the absolute importance weight of quality characteristics,
- W_i represents the comprehensive weight of user need indicators,
- P_{ij} represents the correlation coefficient between user needs and quality characteristics,
- W_k represents the relative importance weight of quality characteristics.

The weight results are then ranked according to their calculated importance.

Correlation	"Strong Correlation"	"Medium Correlation"	"Weak Correlation"	No Correlation
Symbol	●	⦿	**O**	○
Value	5	3	1	0

User Needs	User Needs Comprehensive Weight	Ultrasonic Flaw Detection Module (n1)	Automatic Obstacle Avoidance Module (n2)	Streamlined Exterior (n3)	Recyclable Materials (n4)	Flash Welding Module (n5)	Grinding & Straightening Module (n6)	Brand Identification (n7)	Cleaning System Module (n8)	Quick Disassembly Design (n9)	Terrain-Adaptive Exterior (n10)	Clean Energy (n11)	Remote Control (n12)
		Quality Characteristic											
Inspection Technology C1	0.131	●	**O**	○	**O**	⦿	⦿	**O**	○	○	**O**	**O**	⦿
Cleaning Technology C2	0.059	**O**	○	○	**O**	**O**	**O**	○	●	**O**	○	**O**	⦿
Maintenance TechnologyC3	0.155	⦿	○	○	**O**	●	●	○	○	○	○	**O**	⦿
Safety TechnologyC4	0.089	●	●	**O**	⦿	●	●	○	**O**	**O**	**O**	**O**	⦿
Multi-task Coordination C5	0.061	●	**O**	**O**	○	⦿	⦿	**O**	○	⦿	⦿	**O**	●
Modular AppearanceC6	0.128	⦿	○	**O**	**O**	○	**O**	○	○	●	⦿	⦿	**O**
Brand ImageC7	0.076	**O**	○	**O**	○	○	**O**	●	○	○	○	**O**	○
Industrial AestheticsC8	0.056	**O**	○	●	**O**	**O**	**O**	**O**	○	**O**	○	○	○
Sense of ModernityC9	0.045	**O**	○	⦿	○	○	○	⦿	○	○	○	○	○
Adaptability DesignC10	0.058	⦿	⦿	**O**	⦿	**O**	**O**	○	○	●	●	⦿	**O**
Environmental Friendliness C11	0.063	○	○	**O**	●	⦿	○	○	⦿	⦿	**O**	●	○
IntelligenceC12	0.08	⦿	⦿	○	○	⦿	**O**	○	**O**	⦿	○	⦿	●
Absolute Importance Weight		2.904	1.051	0.89	1.285	2.398	2.253	0.763	0.653	1.746	1.14	1.684	2.193
Relative Importance Weight%		0.153	0.055	0.047	0.068	0.126	0.119	0.04	0.034	0.092	0.06	0.089	0.116

Fig. 3. Quality Function Configuration House for Track Equipment Design

From Figure 3, the importance ranking of track equipment design elements is as follows: n1 > n5 > n6 > n12 > n9 > n11 > n4 > n10 > n2 > n3 > n7 > n8. Therefore, in the product design process, priority should be given to optimizing the quality characteristics related to n1 to ensure that the core design requirements are met. Additionally, design elements with higher importance, such as n5, n6, and n12, should receive adequate attention to enhance overall product performance and user experience.

5 Application of Product Family Theory in Track Equipment Design

5.1 Definition of Track Equipment Product Family

Product family theory emphasizes modularization, standardization, and variability to reduce R&D costs, shorten development cycles, and improve market responsiveness. In track equipment design, adopting a modular design approach ensures consistency within the product family while meeting various operational needs. By integrating QFD (Quality Function Deployment), the relationship between "user needs – technical characteristics" is established, dividing the product family into General Modules and Variable Modules. General Modules: These are fundamental structures and functional units applicable to all track equipment. These modules remain consistent across different models, reducing production and maintenance costs and serving as the primary carrier of the product family’s genetic traits. Variable Modules: These are functional modules customized according to different application needs. They can be flexibly configured to meet various task requirements, enhancing equipment adaptability.

6 Table Type Styles

Table 7. Table Type Styles

	1	***2***	***3***
Finalclusteringcenter	0.13	0.9	0.5
Clustering	4	2	6
Effective		12	

K-means clustering is an unsupervised learning method that classifies similar data points into the same group. This study utilizes AHP-QFD comprehensive evaluation data and SPSS software to cluster the technical characteristic weights of track equipment (see Table 7). The final clustering distribution is 4:2:6, where:General Modules include ultrasonic flaw detection modules, flash welding modules, grinding and straightening modules, and remote control.Variable Modules include quick-detach design and clean energy.Alternative Modules are additional optional features.Among them, variable modules represent the primary genetic characteristics of the track equipment product family.

7 Design Practice

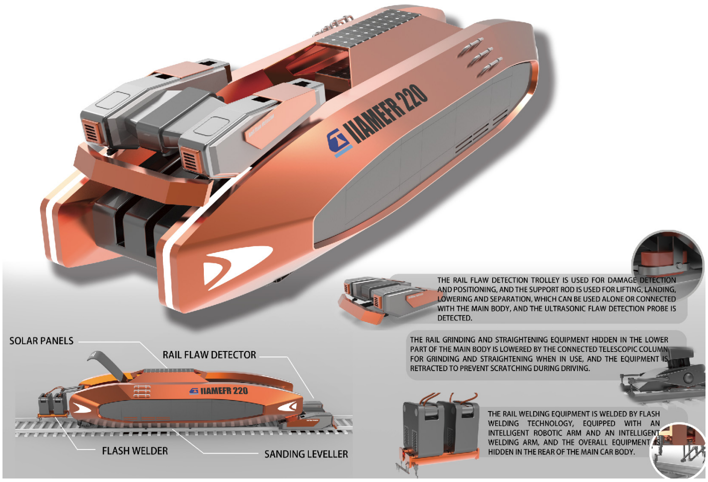

Fig. 4. Track Equipment Design Scheme

Based on the key design indicators and genetic information of track equipment, a systematic design plan is formulated (see Figure 4). The design is mainly divided into two major modules and four devices, including:Flaw Detection Module\Inspection and Maintenance Module\Flaw Detection Trolley\Track Straightening Machine\Track Grinding Machine\Track Welding Machine.The overall structure adopts a detachable design powered by lithium batteries and solar energy. The workflow involves dividing railway segments into multiple sections, with each section equipped with a smart rail flaw detection and maintenance system along with a charging unit for regular inspection and maintenance. This system replaces manual inspection and repair, demonstrating substantial practical value and promising application prospects.

8 Conclusion

This study integrates product family theory with the AHP-QFD method to propose a systematic approach for track equipment product family design. By using AHP (Analytic Hierarchy Process) to calculate user need weights and QFD (Quality Function Deployment) to establish the mapping between needs and technical characteristics, an optimized modular configuration was achieved. K-means clustering further classified technical characteristics into four general modules, two variable modules, and six alternative modules, improving genetic priority matching within the product family. The findings indicate that modular design significantly enhances the universality, flexibility, and scalability of track equipment. The proposed intelligent detection and maintenance system, featuring ultrasonic inspection, welding, grinding, and remote control modules, provides an efficient operational solution. Moreover, a zone-based maintenance strategy is introduced to improve detection accuracy and automation levels. Future research should explore the integration of AI optimization algorithms and IoT (Internet of Things) technology to enhance intelligent monitoring and predictive maintenance capabilities for track equipment. This approach would enable a more efficient, cost-effective rail maintenance system with enhanced automation and intelligence.

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