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Article

A Sustainable Intelligent Design Framework: Integrating AIGC with AHP-QFD-TRIZ for Product Development

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Abstract

In the context of deep AI–design integration, traditional methods struggle to translate multi-source requirements into sustainable engineering solutions while balancing innovation with practicality. This study proposes AQTA, an intelligent design framework that integrates Analytic Hierarchy Process (AHP), Quality Function Deployment (QFD), Theory of Inventive Problem Solving (TRIZ), and AI-Generated Content (AIGC) to enable sustainable product development. AQTA employs a four-stage closed-loop process: requirement analysis, contradiction resolution, solution generation, and validation. QFD and AHP quantify user and sustainability requirements to identify key contradictions, TRIZ resolves technical conflicts and stimulates innovative solutions, while AIGC generates eco-efficient visual concepts through prompt engineering. Multi-criteria decision-making supports evaluation and optimization based on environmental and economic indicators. Empirical studies demonstrate that AQTA significantly enhances innovation quality, design efficiency, and sustainability performance. The framework provides a replicable, hybrid 'theory-driven + AI-generated' methodology, which is validated through the case study of urban fire trucks, contributing to sustainable manufacturing practices in the intelligent era.

Keywords: intelligent design framework; sustainable design; methodology integration; multi-criteria decision-making

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1. Introduction

In recent years, urban fire engines have been upgraded in terms of chassis performance, fire extinguishing systems, rescue equipment, and other functional aspects due to urban development and technological progress. However, the development of exterior styling design is often constrained by the traditional design process [1]. The complexity of fire trucks is reflected in the need to integrate a large number of functional modules and equipment: current design thinking typically prioritizes determining the layout of internal structures and the implementation of core functions first [2]. However, users are no longer limited to a single quest for functionality—the importance of styling design has grown increasingly prominent [3]. Designers are more likely to modify the appearance within the framework of the identified functional layout and structure. Designers are more likely to 'wrap' or modify the appearance within the determined functional layout and structural framework. Due to a lack of systematic and forward-looking consideration of the vehicle's overall visual image, brand identity, and the aesthetic needs of users (including firefighters and the public) in the early stages of the design process, the design within the current market is highly homogeneous. The appearance of different brands and models of vehicles is not distinctive, and less likely to meet the needs of multiple stakeholders [4].

This function- and structure-centric design process, which treats styling as a secondary consideration, means designers lack a basis for considering the impact of styling on brand recognition, public image, and firefighter psychology throughout the conceptual conception, program optimization, and user feedback integration processes [5]. In the face of increasing image requirements for professional equipment in urban emergency response systems, as well as the strategic need for brands to establish a unique image, there is an urgent need to reconstruct the styling design process of fire engines, in order to effectively integrate complex functions with innovative styling. We can learn from user-centered design and branding design strategies and adopt parametric modeling and AIGC (artificial intelligence-generated content), as well as other technologies, to assist with styling exploration [6]. This will enable us to explore technology-driven, design-integrated styling innovations for urban fire trucks, enhancing vehicle styling innovation and accelerating design iteration efficiency.

In the field of mechanical and product design, efficiently capturing user requirements and generating innovative solutions remains a core challenge. Traditional structured methods have made progress in this regard: AHP excels at quantifying and prioritizing user requirements through hierarchical weight calculation [7], while QFD systematically transforms these requirements into technical features via the House of Quality (HOQ). However, both methods have inherent limitations—they primarily focus on ‘identifying what is needed’ (e.g., requirement prioritization, technical feature mapping) but lack direct guidance for ‘how to resolve conflicts’ or ‘generate specific solutions.’ [8]. To compensate, TRIZ has been introduced for its systematic innovation tools (e.g., contradiction matrix, inventive principles) that address technical/physical conflicts in design.

To compensate for the limitations of a single method, researchers have started exploring the combination of multiple traditional methods to improve the integration and problem-solving capabilities of user requirements analysis and innovation design. TRIZ (the Theory of Creative Problem Solving) was introduced for its systematic innovation principles and problem-solving tools, and has been combined with requirements analysis methods such as AHP (Analytical Hierarchy Process) and QFD (Quality Function Deployment) [9]. Some studies have combined QFD with TRIZ, using QFD to identify user needs and technical requirements and construct a House of Quality (HOQ), before using TRIZ to solve technical or physical contradictions in the design process [10]. Alternatively, Chen et al. [11] combined AHP and TRIZ by first quantifying the requirement weights using AHP and then using TRIZ to find optimal solutions for contradictions derived from requirement analysis. They then constructed the Kano–AHP–TRIZ combination model to provide scientific strategies for willow furniture design and promote green innovation in the furniture industry. Other studies have introduced the integration of fuzzy QFD with TRIZ to address requirements uncertainty and identify innovative design solutions [12]. For instance, Martínez-Rojas et al. (2025) incorporated fuzzy logic into the House of Quality (HOQ) of QFD to quantify vague user preferences in complex engineering environments [13], thereby enhancing the robustness of the requirements transformation process under uncertainty. Similarly, Du et al. (2024) introduced behavioral decision theory into QFD, revealing how designers’ cognitive biases influence the prioritization of technical requirements and proposing AI-assisted calibration strategies to mitigate such biases [14]. These studies highlight the necessity of incorporating uncertainty handling and behavioral insights into traditional methodologies. In response, our AIGC-integrated framework leverages large language models to dynamically adjust fuzzy weights and align with user cognitive logic, offering a new pathway to advance these explorations. Although these traditional combinatorial methods [15] have improved the efficiency of requirements transformation and problem solving to some extent and can address design challenges systematically, their application often relies on expert experience. There is still room for improvement in generating completely new and non-traditional design solutions.

In recent years, the rapid development of AI technology, particularly the emergence of generative AI (AIGC), has brought about a new paradigm for product design [16]. AIGC technology has powerful content generation capabilities and can assist designers with concept exploration, style generation, and visual presentation with unprecedented speed and versatility (Figure 1). For instance, AIGC has been used to generate design concepts for an art therapy installation where children with ADHD were encouraged to co-create art with an AI to help improve their attention deficits [17]. This emphasizes the importance of promoting the sustainability of AI in design [18]. Several studies have also focused on optimizing the AI generation process to ensure that its output more accurately reflects the user's intent or emotional needs [19]. The advent of AIGC has significantly broadened the scope of design possibilities, demonstrating significant potential, particularly in creative diffusion and design assistance. However, current applications of AIGC in product design mostly focus on creative assistance and style generation. The challenge of systematically combining AIGC with rigorous user requirements analysis and functional implementation to generate design solutions that are creative and effective in solving practical problems and satisfying users' deep and complex needs remains urgent. Combining structured user requirements analysis methods with the generative capabilities of AIGC is a promising direction for current research. Such explorations aim to leverage the strengths of traditional methods to provide more accurate and structured inputs to AI. It also highlights the potential for collaboration between generative AI and traditional computer-aided design tools. This combination explores the feasibility of using quantitative requirements to guide AI generation, representing an important step towards the development of intelligent design workflows.

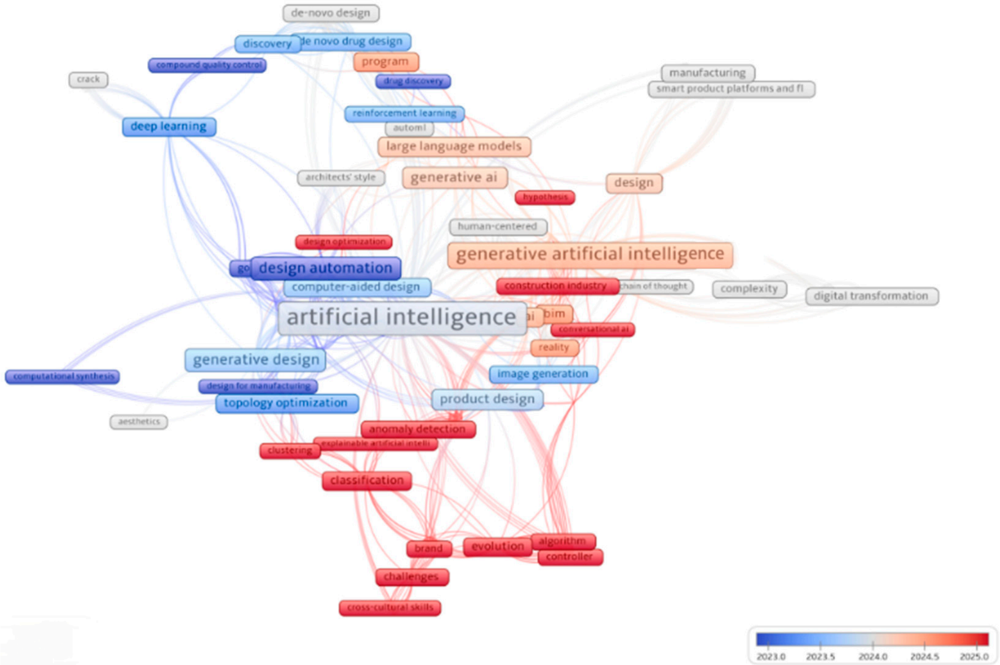


Figure 1. The connection between AI and design in recent years.

On the intelligent and sustainable design of urban fire trucks, this study makes the following key contributions: developing the AQTA (AI-Generated Content (AIGC)–Analytic Hierarchy Process (AHP)–Quality Function Deployment (QFD)–Theory of Inventive Problem Solving (TRIZ)) intelligent design framework to address three key pain points in urban fire truck design, namely inadequate synergy between functionality and styling, low innovation efficiency of traditional methods, and delayed integration of sustainability; validating the effectiveness of the AQTA framework through empirical application in the design of urban rescue fire trucks, with a focus on measurable improvements in design efficiency, innovation quality, and sustainability performance; and realizing product development that balances user orientation, technical feasibility, and environmental friendliness, while establishing a replicable workflow to lay the foundation for the framework's cross-domain application in other emergency equipment.

2. Relevant Theories and Methods

2.1. Generative Artificial Intelligence (GAI)

The development of artificial intelligence, big data, and cloud computing has given rise to various generative artificial intelligence (GAI) models [20], transforming AI technology from a traditional data analysis tool into a cognitive engine capable of autonomous creation. Through Adversarial Generative Networks (GANs) [21], Diffusion Models [22] and Transformer Architecture, generative artificial intelligence achieves end-to-end generative capabilities from requirements to design. Consequently, computers' ability to mimic human understanding, thinking, and learning has significantly improved, enabling AI to participate in design activities in a smarter and more creative manner, and to become a new type of design material and production method [23]. The multimodal capability of generative AI can simulate the way the human brain processes information by integrating different perceptual modalities (e.g., text, images, audio, video, EEG, physiological, and other data), achieving comprehensive information understanding and generation [24]. During the concept generation stage, AI technology is expected to analyze a wide range of user data in order to gain a comprehensive understanding of consumer preferences. These insights are then translated into specific product design parameters and visual representations. This process helps to ensure that subsequent design work is more relevant to the actual needs of users. AI can support designers and users in expressing creative ideas through natural and diverse interactions, as well as manipulating machine-generated design solutions [25]. This approach helps capture subtle or fleeting sparks of inspiration and greatly reduces the technical barriers to using complex design tools, enabling more people to participate in the creative process. This enhances flexibility and creativity in the design process, promoting engagement among a wider group of people [26].

Artificial Intelligence-Generated Content (AIGC) refers to content generated through generative AI (GAI) technologies that can efficiently produce high-quality design data in the form of text, images, audio, video, and analog sensor data [27,28]. As user expectations rise and product complexity increases, there is a growing need for multidisciplinary approaches that combine different categories of AI-generated data to deliver more effective solutions [29]. Since the Diffusion Model broke through in 2020, its ability to generate high-fidelity images through progressive denoising has greatly enhanced the diversity and controllability of the content it produces. Examples include the Stable Diffusion system, released in 2022, which can generate industrial design solutions that are both functional and aesthetically pleasing based on semantic descriptions such as 'cyberpunk style first aid kit' [30]. By constructing a 'requirement-programme' probability mapping space, non-professional users can participate in complex product development in a natural, interactive way, marking the arrival of a new era of human–computer collaborative design [31]. At its core, this system employs a probabilistic generative model structured in three layers to enable human–AI collaborative creation: the bottom layer uses Bayesian networks to parse multimodal user intent into probabilistic parameters; the middle layer employs reinforcement learning to dynamically optimize the model based on feedback; the top layer integrates human expertise with AI computation to output solutions through probabilistic weighting. This framework transforms creative processes into quantifiable probabilistic interactions, upgrading artistic design from experience-driven to data-driven engineering, achieving efficient and controllable human–machine innovation (Figure 2).

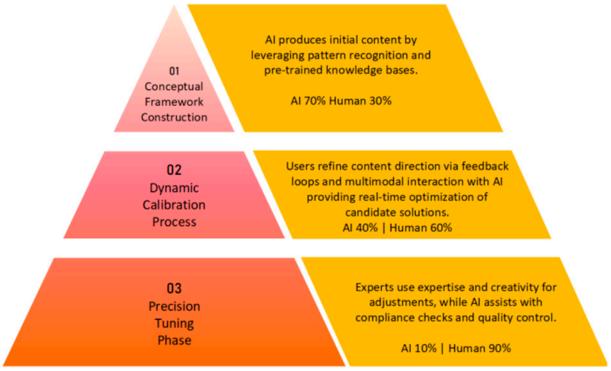


Figure 2. Hierarchical probabilistic collaborative generation architecture.

2.2. Traditional Design Methods

The Analytic Hierarchy Process (AHP) is a multi-criteria decision-making method (Table 1). It is based on the principle of establishing a hierarchical structure to decompose complex problems. Through the judgment matrix, it calculates the relative weight of each factor. It is widely used in program evaluation and priority ranking. Step 1: Invite industry experts to score the first- and second-level indicator demands two by two and construct a demand judgment matrix. Step 2: Calculate the user demand weight using the arithmetic or geometric mean, or other methods, and use a one-time test to verify the reliability and reasonableness of the results [32].

Table 1. The 9-point scale system for Analytic Hierarchy Process (AHP).

Scale Value	Definition
1	Equally important: two criteria contribute equally to the objective.
3	Slightly more important: one criterion is marginally more important than another.
5	Moderately more important: a clear preference for one criterion over another.
7	Strongly more important: a demonstrated importance difference between criteria.
9	Extremely more important: a pronounced and overriding importance difference.
2, 4, 6, 8	Intermediate values: reflect compromises between adjacent qualitative judgments.

QFD (Quality Function Deployment) is a systematic approach to ensuring product design quality. The weight of each index is derived through the theory of hierarchical analysis. Secondly, the core function of QFD, the Quality House, is used to transform the requirements corresponding to the three levels of indicators. Figure 1 shows the quality house model [33], which can be used to display the correlation matrix of product characteristics graphically, thus deriving the importance and correlation between each parameter. According to the user demand weights and the two-by-two scoring of each technical indicator, a corresponding score is calculated for each product characteristic. The numbers on the body of the Quality House show the correlation relationship: ‘1’ indicates weak correlation, ‘3’ indicates medium correlation, ‘5’ indicates strong correlation and a blank indicates no correlation. The number 1 indicates weak correlation, the number 3 indicates moderate correlation, the number 5 indicates strong correlation and a blank indicates no correlation. The Quality House model is used to derive the relative weights of the product feature outputs. The roof of the quality house uses '+' and '−' symbols to represent positive and negative correlations between two technical demand indicators: '+' represents positive correlation, '−' represents negative correlation. A '−' symbol indicates a negative correlation and a blank indicates no correlation.

TRIZ (the Theory of Inventive Problem Solving) is a systematic innovation methodology founded by the Soviet scientist Genrich Altshuller in 1946. It reveals the laws of technological system evolution and establishes a mechanism for resolving contradictions. Through the analysis of 2.5 million invention patents worldwide, TRIZ has developed a multi-layered system of tools comprising a matrix of technological contradictions, the principle of the separation of physical contradictions, a physical field analysis model, and 76 standard solutions. TRIZ has become a core paradigm for innovation in complex engineering systems and is widely used in engineering design, product development, and other innovative work [34]. The essence of TRIZ lies in identifying and resolving contradictions within a system. Through a series of principles and tools, TRIZ transforms complex problems into standard problems and seeks standardized solutions [35].

2.3. Design of an Integrated Platform Architecture Based on AIGC and Traditional Methods

2.3.1. Design Framework

Although AIGC and traditional design methods have their own advantages, the urgent problem of how to deeply integrate the two to form a complete, intelligent, iterative, closed-loop design workflow covering everything from requirements analysis to solution evaluation has yet to be solved. Existing research either focuses on applying AIGC to a specific part of the design process or explores limited integration of traditional methods. Few studies have built a unified platform that uses AIGC's intelligence to overcome the limitations of traditional methods in data processing, idea generation, and method linkage. This platform automates and intelligently synergizes the entire design process through intelligent workflows and ultimately forms a closed-loop design workflow capable of evaluation and feedback (Figure 3). Specifically, the problem is how to use AIGC to empower AHP data input and analysis, QFD correlation construction, and contradiction identification, and TRIZ solution generation and application under an integrated framework. The aim is to achieve seamless linkage of each stage and intelligent evaluation and feedback of the results in order to build a complex design platform that is more efficient, intelligent, and innovative than existing methods. A domain knowledge base can be created by integrating historical design cases and multidisciplinary simulation data to support sample-less generation [36].

2.3.2. AIGC Human–Computer Collaborative Design Service Process

Through an overview of the basic theories of AIGC, AHP, QFD, and TRIZ, the design process is constructed in the following stages (Figure 4).

Stage 1: Provide relevant analysis words through GPT4 and Deepseek to obtain user preferences and use AHP hierarchical analysis to build a user requirement hierarchy model to classify the requirements at each level. Construct the demand model for each indicator level and calculate the user weights.

Stage 2: Import the user requirements and weights into the quality house in the QFD quality function configuration theory, so as to obtain the relationship matrix between user requirements and technical requirements.

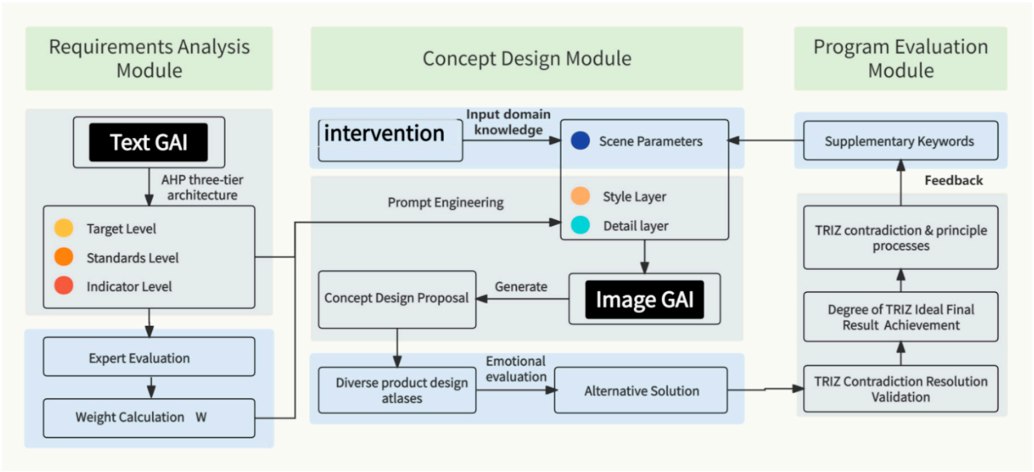


Figure 3. Human–AI co-creation with AHP-QFD-TRIZ system.

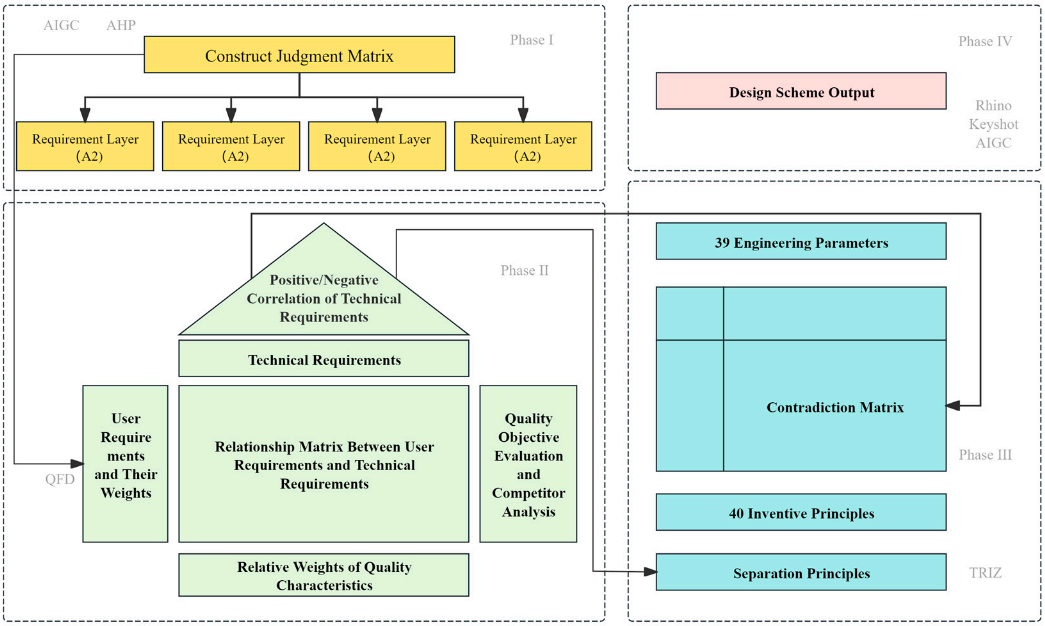


Figure 4. Design flow chart.

Stage 3: Combine AIGC's data-driven and pattern recognition capabilities with TRIZ's systematic innovation methodology to provide designers with more efficient and innovative design tools, thereby accelerating the design of the initial eco-innovation solution, through a series of physical and technological conflict analyses corresponding to the 39 standard conflict parameters and 40 problem-solving invention principles, to analyze and solve the specific conflict principles and solutions.

Stage 4: Transform each user requirement, model, and conflict solution obtained above into design practice, and design and develop the product solution. Obtain the cue words for generating a rescue fire engine and generate a reference that matches the target intent. Using industrial design software Rhino 6.0 and KeyShot 2023, model building and product rendering are carried out to obtain the final solution of the product. The flowchart is shown in Figure 2. They can optimize the traditional design process from 'investigation' to 'concept design' to 'detailed design' to 'rendering design'. The text-generation AI ChatGPT 4 can provide imagery adjectives suitable for describing the target product during the investigation phase. Midjourney, an image-generating AI, can generate forms for the target product in the conceptual and detailed design phases [37].

2.3.3. AI-IDN Complex Vehicle Design Platform

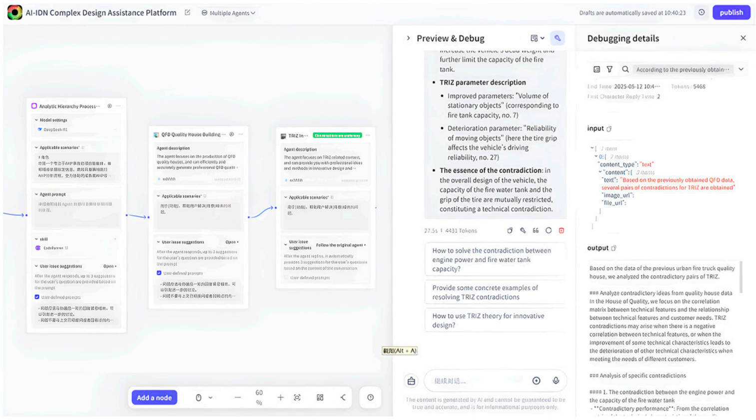
The platform AI-IDN (AI-Intelligent Design Nexus) is designed as a modular system (see Figure 3) comprising multiple specialized intelligent agents. These agents, which are implemented using frameworks such as Coze, have specific capabilities, knowledge bases, and interaction logics that enable them to perform different tasks throughout the design workflow. This modular structure facilitates system development and maintenance, as well as flexible workflow orchestration [38] (Figure 5a).

Workstream 1: AIGC-Enhanced User Requirements Prioritization

Workflow 1 (AHP + AIGC), led by the Requirements Analysis Agent, centers using the Analytical Hierarchy Process (AHP) to systematically capture and quantitatively prioritize user requirements. This lays the data foundation for the subsequent design phase. The platform uses the capabilities of AIGC, especially large language models (LLMs) [39], to make AHP preparation and execution more efficient [40]. AIGC helps users decompose complex requirements into logical hierarchical structures and intelligently generates questionnaire prompts for pairwise comparisons, optimizing the data collection process. The Requirements Analysis Agent then receives the data, constructs the judgment matrix, and performs standard AHP calculations to determine the requirements' weights. AIGC assists with consistency checking and flags key comparisons in case of judgmental bias. It also supports users in optimizing their inputs. The output of this phase is a prioritized list of user requirements with calculated weights (Figure 5b).

Workstream 2 (AHP Results → QFD + AIGC)

Building on the output of Workstream 1, Workstream 2 is carried out by the Requirements Transformation Agent. This agent uses Quality Function Deployment (QFD) to translate prioritized customer requirements into technical features that can be implemented, and to identify potential technical conflicts. The agent imports the weighted customer requirements and directs the creation of the House of Quality (HOQ). The key is establishing a correlation matrix between customer requirements and technical characteristics. AIGC analyses textual descriptions and existing knowledge to intelligently assist with judging and recommending relationship strengths, which significantly improves the efficiency and accuracy of HOQ construction. The agent derives the importance weights of technical features based on the HOQ's complete QFD calculation and identifies potential technical contradictions or conflicts with negative correlations using the HOQ's roofing matrix. The output of this workflow is a prioritized list of technical features with importance weights, as well as an identification of key technical conflicts (Figure 5c).



further limit the capacity of the fire tank.

- **TRIZ parameter description**
  - Improved parameters: "Volume of stationary objects" (corresponding to fire tank capacity, no. 7)
  - Deterioration parameter: "Reliability of moving objects" (here the tire grip affects the vehicle's driving reliability, no. 27)
- **The essence of the contradiction**: in the overall design of the vehicle, the capacity of the fire water tank and the grip of the tire are mutually restricted, constituting a technical contradiction.

27.5s | 4431 Tokens

How to solve the contradiction between engine power and fire water tank capacity?

Provide some concrete examples of resolving TRIZ contradictions

How to use TRIZ theory for innovative design?

The content is generated by AI and cannot be guaranteed to be true and accurate, and is for informational purposes only.

According to the previously obtain···

End Time 2025-05-12 10:4··· Tokens : 5468
First Character Reply Time 2

input

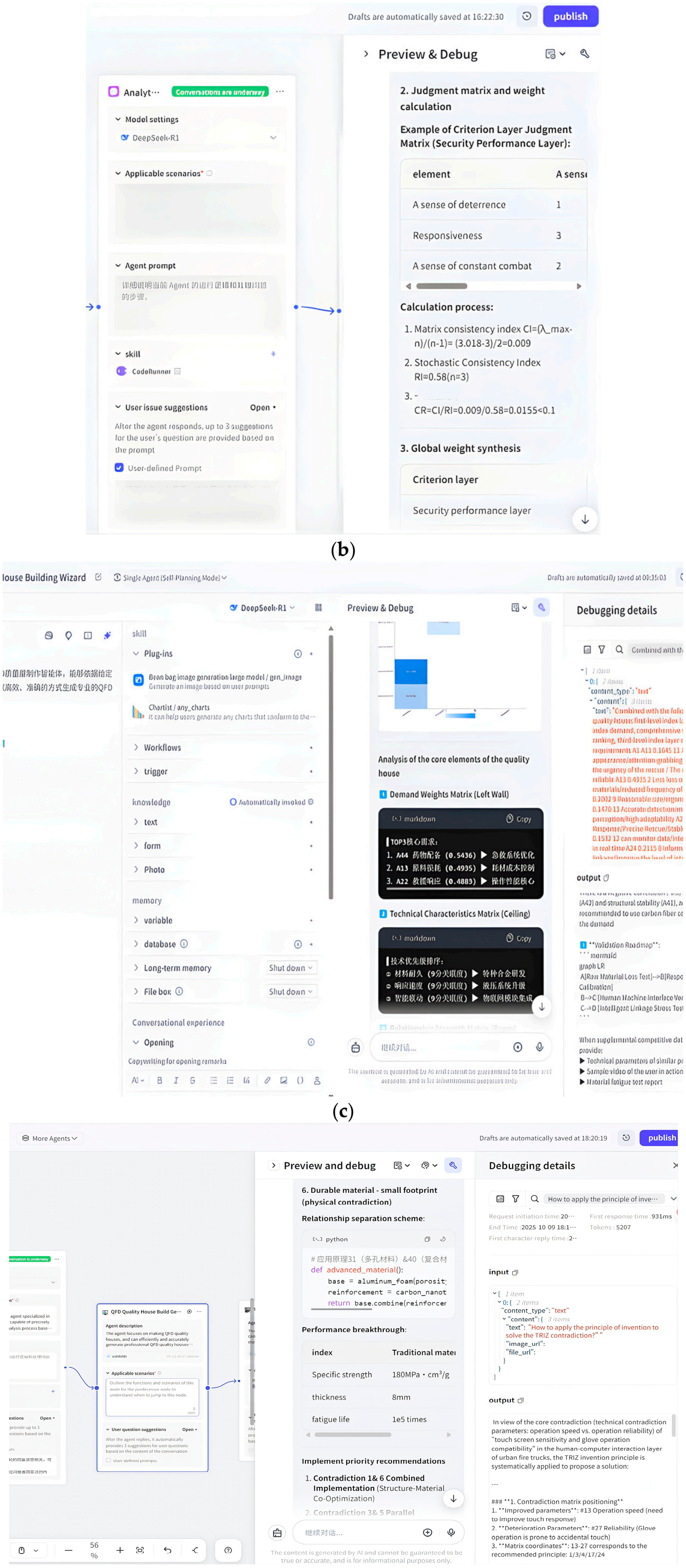
```
[ 1 item
  0:[ 2 items
   "content_type":"text"
   "content":[ 3 items
    "text": "Based on the previously obtained QFD data, several pairs of contradictions for TRIZ are obtained"
    "image_url":
    "file_url":
    ]
  ]
]
```

output

```
Based on the data of the previous urban fire truck quality house, we analyzed the contradictory pairs of TRIZ.

### Analyze contradictory ideas from quality house data
In the House of Quality, we focus on the correlation matrix between technical features and the relationship between technical features and customer needs. TRIZ contradictions may arise when there is a negative correlation between technical features, or when the improvement of some technical characteristics leads to the deterioration of other technical characteristics when meeting the needs of different customers.

### Analysis of specific contradictions

#### 1. The contradiction between the engine power and the capacity of the fire water tank
- **Contradictory performance**: From the correlation
```

(**a**)

Figure 5. *Cont.*



After the agent responds, up to 3 suggestions for the user's question are provided based on the prompt

Preview & Debug

2. Judgment matrix and weight calculation

Example of Criterion Layer Judgment Matrix (Security Performance Layer):

element	A sens
A sense of deterrence	1
Responsiveness	3
A sense of constant combat	2

Calculation process:

1. Matrix consistency index CI=(λ_max-n)/(n-1)= (3.018-3)/2=0.009
2. Stochastic Consistency Index RI=0.58(n=3)
3. - CR=CI/RI=0.009/0.58=0.0155<0.1

3. Global weight synthesis

Criterion layer
Security performance layer

(b)

Analysis of the core elements of the quality house

Demand Weights Matrix (Left Wall)

```
TOP3核心需求:
1. A44 药物配备 (0.5436) ▶ 急救系统优化
2. A13 原料损耗 (0.4935) ▶ 耗材成本控制
3. A22 数据响应 (0.4883) ▶ 操作性能核心
```

Technical Characteristics Matrix (Ceiling)

```
技术优先级排序:
○ 材料耐久 (9分关联度) ▶ 轻钟合金研发
○ 响应速度 (9分关联度) ▶ 液压系统升级
○ 智能联动 (9分关联度) ▶ 物联网模块集成
```

(c)

6. Durable material - small footprint (physical contradiction)

Relationship separation scheme:

```python
# 应用原理31（多孔材料）&40（复合材
def advanced_material():
    base = aluminum_foam(porosit
    reinforcement = carbon_nanot
    return base.combine(reinforcen
```

Performance breakthrough:

index	Traditional mate
Specific strength	180MPa · cm³/g
thickness	8mm
fatigue life	1e5 times

Implement priority recommendations

1. **Contradiction 1& 6 Combined Implementation** (Structure-Material Co-Optimization)
2. Contradiction 3& 5 Parallel

The content is generated by AI and cannot be guaranteed to be true or accurate, and is for informational purposes only.

Request initiation time:20··· First response time :931ms
End Time :2025 10 09 18:1··· Tokens : 5207
First character reply time :2··

input

```
[ 1 item
  0:{ 2 items
   "content_type":"text"
   "content":{ 3 items
    "text": "How to apply the principle of invention to solve the TRIZ contradiction?" "
    "image_url":
    "file_url":
   }
  }
]
```

output

```
In view of the core contradiction (technical contradiction parameters: operation speed vs. operation reliability) of "touch screen sensitivity and glove operation compatibility" in the human-computer interaction layer of urban fire trucks, the TRIZ invention principle is systematically applied to propose a solution:

---

### **1. Contradiction matrix positioning**
1. **Improved parameters**: #13 Operation speed (need to improve touch response)
2. **Deterioration Parameters**: #27 Reliability (Glove operation is prone to accidental touch)
3. **Matrix coordinates**: 13-27 corresponds to the recommended principle: 1/3/4/17/24
```

(d)

Figure 5. (**a**) AI-IDN Complex Vehicle Design Platform. (**b**) AI-IDN Complex Vehicle Design Platform (AHP + AIGC). (**c**) AI-IDN Complex Vehicle Design Platform (QFD + AIGC). (**d**) AI-IDN Complex Vehicle Design Platform (TRIZ + AIGC).

Workflow 3 (QFD Results → TRIZ + AIGC)

Based on the key technical characteristics and contradictions identified in Workstream 2, Workstream 3 is led by the Innovation Generation Agent. This agent applies TRIZ theory for systematic problem solving and uses AIGC to generate innovation concepts. The agent extracts engineering paradoxes from the QFD results and uses AIGC to convert these into TRIZ engineering parameters, inspiring and explaining the associated inventive principles. By integrating information on the paradox, parameter and principle, AIGC can generate preliminary design concepts, sketches or detailed descriptions with unprecedented speed and diversity. This involves exploring innovative solutions that apply different TRIZ principles to address the identified technical challenges and high-priority requirements. The output of this phase is a series of preliminary design concepts (Figure 5d).

2.4. AI Ethics Compliance

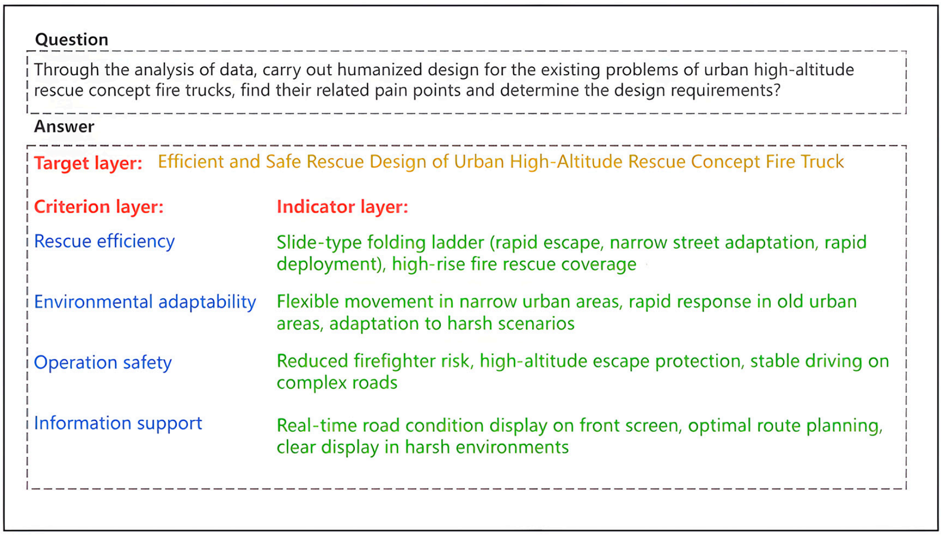
Throughout the entire process of using AI-Generated Content (AIGC) tools in this study, strict adherence to core ethical norms is maintained, specifically covering three aspects. First, for data privacy protection: all information containing personal or institutional identifiers in the multi-source data used for requirement analysis (e.g., interview records of frontline firefighters, equipment demand questionnaires from urban fire stations) has been fully anonymized, and the data are exclusively used for the requirement analysis phase of this study. Second, for compliant use of AIGC tools: when using ChatGPT (for requirement decomposition and questionnaire generation) and Midjourney (for design concept sketching), their official service agreements are strictly followed; all AI-generated content is clearly labeled as 'AI-assisted generation' in the study to avoid conflating human-created outcomes with AI-assisted ones. Third, for bias mitigation and result calibration: to prevent AI outputs from being skewed by biases in training data (e.g., overemphasizing visual aesthetics while neglecting the safety priority of firefighting equipment), a dual-calibration mechanism is established—specifically, a review panel composed of fire engineering experts and design ethics scholars is invited to cross-validate AI-generated results (such as requirement weights and TRIZ principle matching outcomes), ensuring that core functions meet the safety ethics requirements of the industry.

3. Experiments and Case Studies

Experimental design: a city fire engine as an example. Through field research at a city fire station and expert interviews with the equipment division and the first-line shift supervisor, we gained an understanding of the current state of fire truck research, derived key demand points, and recorded them systematically. We then combined this information with questionnaire data and discussed it with ChatGPT and DeepSeek, respectively, to summarize user requirements for urban concept fire trucks, and generative artificial intelligence technology was used to analyze and mine the requirement data. Using the hierarchical analysis method, the requirements were classified and graded to filter out the hierarchical model that best met emotional needs. Generative AI assistance improves the science and accuracy of model construction and provides intelligent support for the emotional design of urban rescue fire engines.

3.1. User Perceptual Needs Analysis Based on GPT4

Based on the natural language processing capabilities of ChatGPT 4.0, multi-source data were systematically captured and analyzed to construct an AHP three-tier architecture for innovative fire truck design. The study first utilized DeepSeek to collect over a hundred recent academic papers covering topics such as fire truck design, emergency rescue equipment, and intelligent firefighting systems, while also integrating feedback from frontline firefighters, industry standard documents, and technical information of advanced domestic and international vehicle models. Through in-depth analysis of multi-source data, professional terminology and innovative design directions were extracted. Sentiment analysis methods were applied to process practical evaluations from firefighters, identifying shortcomings in existing vehicles and potential needs. The functional parameters of competing products were deconstructed to summarize key technical indicators and human-centric design elements, forming a demand word matrix across four dimensions: functionality, efficiency, human factors, and environment. On this basis, the Analytic Hierarchy Process (AHP) was employed to establish a standardized demand structure: the goal layer defines the product positioning centered on efficient emergency rescue; the criterion layer establishes core dimensions such as functionality, operational efficiency, technical feasibility, and environmental adaptability; the indicator layer refines these dimensions into quantifiable and verifiable specific indicators, including rapid response capability, modular multi-disaster response systems, intelligent fire scene perception systems, and complex terrain mobility, providing a systematic, data-driven demand framework for the new generation of fire truck design (Figure 6). The layers that match the content are filtered out in order to construct the user affective hierarchical model of the city rescue fire engine concept (Figure 7).



Question

Through the analysis of data, carry out humanized design for the existing problems of urban high-altitude rescue concept fire trucks, find their related pain points and determine the design requirements?

Answer

Target layer: Efficient and Safe Rescue Design of Urban High-Altitude Rescue Concept Fire Truck

Criterion layer:	**Indicator layer:**
Rescue efficiency	Slide-type folding ladder (rapid escape, narrow street adaptation, rapid deployment), high-rise fire rescue coverage
Environmental adaptability	Flexible movement in narrow urban areas, rapid response in old urban areas, adaptation to harsh scenarios
Operation safety	Reduced firefighter risk, high-altitude escape protection, stable driving on complex roads
Information support	Real-time road condition display on front screen, optimal route planning, clear display in harsh environments

Figure 6. The humanized design of the urban high-altitude rescue concept fire truck extracts the relevant pain points and the case display of design needs.

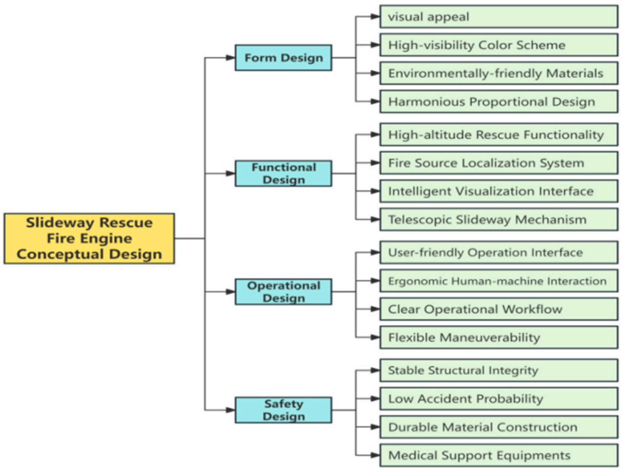


Figure 7. Hierarchical model of user emotional needs for conceptual high-altitude rescue fire trucks.

3.2. AHP-Based Construction of Demand Weighting Matrix

Judgment matrices for the first-level and second-level indicators of the user requirement hierarchy in the aerial rescue fire truck conceptual design were constructed (as shown in Tables 2–4). Using the Analytic Hierarchy Process (AHP), the relationships between the weights of these indicators were calculated. A consistency check was performed by introducing the average consistency index (CI) to validate the reliability and rationality of the results. The matrices and computational outcomes for all second-level indicators are presented in Tables 5–7.

Table 2. Indicator (A1~A4) judgment matrix.

A	A1	A2	A3	A4
A1	1	1/2	2	1/3
A2	2	1	2	1/3
A3	1/2	1/2	1	1/2
A4	3	3	2	1

Table 3. Analytic Hierarchy Process calculation results.

Metrics	**Eigenvector (Math.)**	**Weights**	**Maximum Eigenvalue**	**CI**	**RI**	**CR**
A1	0.693	0.1733	4.215	0.072	0.882	0.081
A2	0.947	0.2368				
A3	0.551	0.1376				
A4	1.809	0.4522				

Table 4. Requirement element (A11~A14) judgment matrix under A1.

A1	A11	A12	A13	A14
A11	1	6	4	5
A12	1/6	1	1	1
A13	1/4	1	1	1
A14	1/5	1	1	1

Table 5. Requirement element (A22~A25) judgment matrix under A2.

A2	A21	A22	A23	A24
A21	1	1/3	1/2	1
A22	3	1	5	2
A23	2	1/5	1	1/2
A24	4	1/2	2	1

Table 6. Requirement element (A31~A34) judgment matrix under A3.

A3	A31	A32	A33	A34
A31	1	2	1	1
A32	1/2	1	1/2	1
A33	1	2	1	1
A34	1	4	1	1

Table 7. Judgment matrix for requirement elements (A41~A44) under A4.

A4	A41	A42	A43	A44
A41	1	1/2	1/4	1/5
A42	2	1	1/3	1/5
A43	4	3	1	1/3
A44	5	5	3	1

Based on calculations using the matrix weighting formula, the results indicated, λ_{max} = 4.215, CI = 0.072, RI = 0.882, CR = 0.081 < 0.1. The judgment matrices for all first-level indicators were found to satisfy the consistency check criteria, demonstrating credibility.

Based on calculations using the matrix weighting formula, the results indicated, λ_{max} = 4.016, CI = 0.005, RI = 0.882, CR = 0.006 < 0.1. All demand elements under second-level indicator A1 were found to satisfy the consistency check criteria, thereby demonstrating credibility.

Based on calculations using the matrix weighting formula, the results indicated, λ_{max} = 4.231, CI = 0.077, RI = 0.882, CR = 0.087 < 0.1. All demand elements under second-level indicator A2 were found to satisfy the consistency check criteria, thereby demonstrating credibility.

Based on calculations using the matrix weighting formula, the results indicated, λ_{max} = 4.061, CI = 0.020, RI = 0.882, CR = 0.023 < 0.1. All demand elements under second-level indicator A3 were found to satisfy the consistency check criteria, thereby demonstrating credibility.

Based on calculations using the matrix weighting formula, the results indicated, λ_{max} = 4.111, CI = 0.037, RI = 0.882, CR = 0.042 < 0.1. All demand elements under second-level indicator A1 were found to satisfy the consistency check criteria, thereby demonstrating credibility.

3.3. Translating User Demands into Design Specifications via QFD

Based on the hierarchical user demands and the prioritized comprehensive weights derived from AHP, a transformation analysis was performed to convert the technical specifications of the high-altitude rescue fire truck. The results are summarized in Table 8.

Through the transformation of demands corresponding to each indicator hierarchy, the requirements for the slide rescue fire truck can be categorized into three layers: body, components, and overall design (as shown in Figure 8). Body design priorities: structural stability, material durability, and high-altitude rescue assistive devices. Component design priorities: flexibility, multi-stage telescopic slides, multifunctionality, and replaceable modular configurations. Overall design priorities: human–machine interface (HMI), futuristic aesthetics, streamlined visual language, and ergonomic rationality.

Analyzed through the Quality House (Figure 9): material durability (5.417) > operational flexibility (4.3141) > multifunctionality (3.9991) > replaceable modular configurations (3.4328) > multi-stage telescopic slides (3.4236) > AI-assisted devices (2.8825) > futuristic aesthetics (2.6468) > ergonomic rationality (2.041) > structural stability (1.9766) > human–machine interface (HMI) (1.7366) > compact footprint (1.1614) > streamlined visual language (0.5833).

Table 8. Conversion of corresponding requirements for each indicator layer.

Primary Criteria	Secondary Sub-Criteria	Comprehensive Weight	Weight Ranking	Tertiary Requirements
A1	A11	0.1645	11	Aesthetically appealing design/Visually striking
	A12	0.1418	14	Urgency-compliant rescue operations/High-visibility and reliable color schemes
	A13	0.4935	2	Minimal material wear/Reduced replacement frequency
	A14	0.2002	9	Ergonomic structure sizing/Human–machine compatibility
A2	A21	0.1470	13	Accurate detection/Multi-directional sensing/High adaptability
	A22	0.4883	3	Rapid response/Precise rescue operations/Stability and safety
	A23	0.1532	12	Real-time data monitoring/Intelligent data transmission
	A24	0.2115	8	Information interoperability/Enhanced intelligence integration
A3	A31	0.2887	4	Short training cycles/ User-friendly operation
	A32	0.1756	10	Comfortable seating/Wide visibility/Intuitive controls
	A33	0.2887	4	Simplified workflows/ Operational efficiency
	A34	0.2470	7	High adaptability/ Mobility optimization
A4	A41	0.0764	16	Robust structural design/Ergonomic compliance
	A42	0.1150	15	Lightweight construction/Recyclable and transport-friendly materials
	A43	0.2649	6	Advanced material selection
	A44	0.5436	1	Medical supply integration/ Emergency healthcare readiness

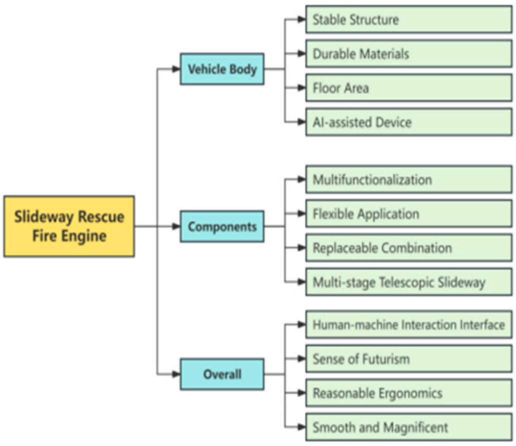
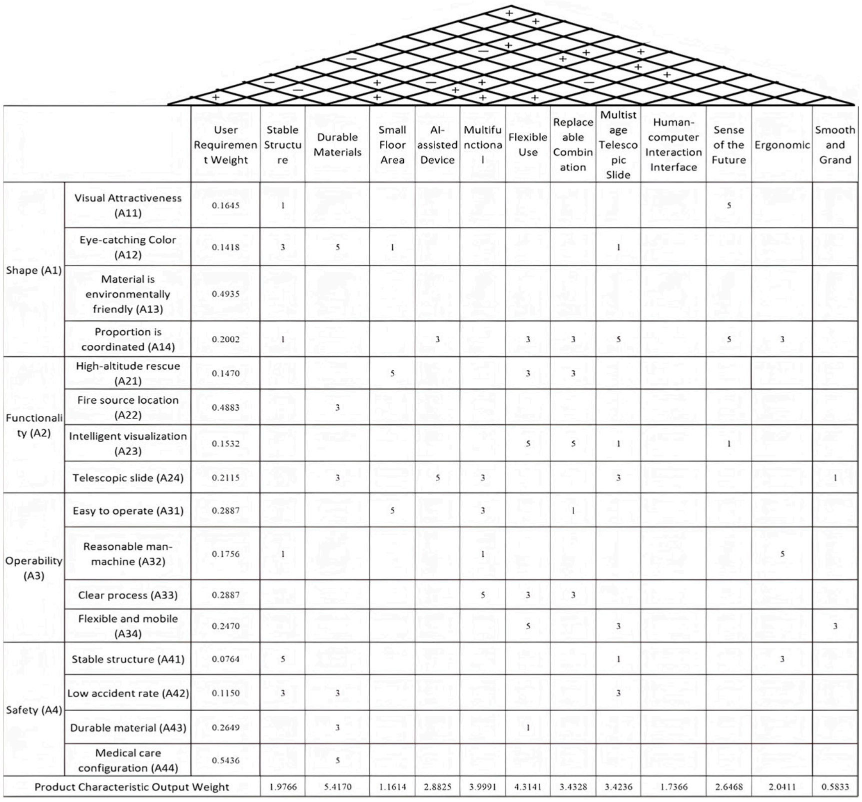


Figure 8. AI-IDN Complex Vehicle Design Platform.



		User Requirement Weight	Stable Structure	Durable Materials	Small Floor Area	AI-assisted Device	Multifunctional	Flexible Use	Replaceable Combination	Multistage Telescopic Slide	Human-computer Interaction Interface	Sense of the Future	Ergonomic	Smooth and Grand
Shape (A1)	Visual Attractiveness (A11)	0.1645	1									5		
	Eye-catching Color (A12)	0.1418	3	5	1					1				
	Material is environmentally friendly (A13)	0.4935												
	Proportion is coordinated (A14)	0.2002	1			3		3	3	5		5	3	
Functionality (A2)	High-altitude rescue (A21)	0.1470			5			3	3					
	Fire source location (A22)	0.4883		3										
	Intelligent visualization (A23)	0.1532						5	5	1		1		
	Telescopic slide (A24)	0.2115		3		5	3			3				1
Operability (A3)	Easy to operate (A31)	0.2887			5		3		1					
	Reasonable man-machine (A32)	0.1756	1				1						5	
	Clear process (A33)	0.2887					5	3	3					
	Flexible and mobile (A34)	0.2470						5		3				3
Safety (A4)	Stable structure (A41)	0.0764	5							1			3	
	Low accident rate (A42)	0.1150	3	3						3				
	Durable material (A43)	0.2649		3				1						
	Medical care configuration (A44)	0.5436		5										
Product Characteristic Output Weight			1.9766	5.4170	1.1614	2.8825	3.9991	4.3141	3.4328	3.4236	1.7366	2.6468	2.0411	0.5833

Figure 9. House of Quality model of urban fire trucks.

3.4. TRIZ-Based Contradiction Analysis and Resolution for Design Key Points

3.4.1. Contradiction Analysis

By integrating the TRIZ theory of inventive problem solving with the QFD House of Quality (HoQ), the positive/negative correlations between technical requirements for the aerial rescue fire truck concept are visually identified through the HoQ's 'roof' section. Six critical contradictions are derived:

Contradiction 1: Structural stability vs. compact footprint. Enhancing structural reinforcement at critical positions to ensure operational safety necessitates increased vehicle footprint.

Contradiction 2: Structural stability vs. multifunctionality. Adding functional complexity compromises structural integrity and safety.

Contradiction 3: Rapid deployment vs. space efficiency. Rapid deployment requires complex expansion mechanisms (increasing volume), while compactness demands structural simplification (reducing deployment efficiency), forming a time–space physical contradiction.

Contradiction 4: Multifunctionality vs. streamlined aesthetics. Achieving intelligent automation introduces exterior complexity, conflicting with visual simplicity.

Contradiction 5: Automated systems vs. minimalist design. Minimizing footprint drastically reduces functional capabilities.

Contradiction 6: Material durability vs. compact footprint. Durable materials require increased thickness/density (expanding footprint), whereas space constraints demand lightweighting (reducing durability), creating a strength–volume physical contradiction.

Using TRIZ methodologies and its inventive principles, these six contradictions are systematically categorized, and corresponding recommended resolution principles are summarized in Table 9.

Table 9. Contradictions and corresponding invention principles.

Contradiction Pair	Contradiction Type	Improved Parameter	Worsened Parameter	Corresponding Inventive Principles
Structural Stability vs. Compact Footprint	Technical Contradiction	13-Stability of Structure	6-Area of Stationary Object	3-Local Quality/ 5-Combining/17-Change in Dimensionality/29-Pneumatics or Hydraulics
Structural Stability vs. Multifunctionality	Technical Contradiction	13-Stability of Structure	35-Adaptability or Versatility	3-Local Quality/5-Combining/ 6-Multifunctionality/ 17-Change in Dimensionality
Rapid Deployment vs. Space Efficiency	Technical Contradiction	25-Time Loss	5-Area of Stationary Object	10-Preliminary Action/ 15-Dynamicity/ 17-Change in Dimensionality/ 28-Replacement of Mechanical System
Multifunctionality vs. Streamlined Aesthetics	Technical Contradiction	35-Adaptability or Versatility	12-Shape	2-Extraction/3-Local Quality/4-Asymmetry/ 6-Multifunctionality
Automated Systems vs. Minimalist Design	Physical Contradiction	Separation Principle (Spatial)		1-Segmentation/ 2-Extraction/3-Local Quality/4-Asymmetry/ 7-Nesting/17-Change in Dimensionality
Material Durability vs. Compact Footprint	Physical Contradiction	Separation Principle (Conditional)		3-Local Quality/17-Change in Dimensionality/ 31-Porous Materials/40-Composite Materials

3.4.2. Contradiction Resolution

Solution 1: To address the conflict between structural stability and compact footprint, the inventive principles of Local Quality and Combining are applied. Integrate multiple functional modules into a compact design, such as employing foldable or telescopic support structures. These structures expand during operations to ensure stability and retract during non-operational states to minimize space occupancy.

Solution 2: For the contradiction between structural stability and multifunctionality, principles like Extraction and multifunctionality are utilized. Develop modular components (e.g., detachable rescue equipment such as slides and platforms) to enable rapid reconfiguration based on mission requirements. Enhance versatility by integrating auxiliary safety features (e.g., anti-slip strips, guardrails) or additional tools (e.g., ropes, life rings) into the slide system, allowing single devices to adapt to diverse rescue scenarios.

Solution 3: To resolve the rapid deployment vs. space efficiency conflict, principles such as Combining and multifunctionality are adopted. Implement a segmented design for functional modules (e.g., rescue slides, vehicle body, auxiliary devices) to enable flexible assembly. For instance, rescue slides can be folded for storage when unused, and the vehicle body can feature detachable sections to optimize transport and storage efficiency.

Solution 4: For the multifunctionality vs. streamlined aesthetics contradiction, principles like Segmentation and Extraction are applied. Decompose complex automated systems into independent yet coordinated subsystems, each dedicated to specific functions, thereby simplifying exterior design while maintaining visual coherence. Critical components (e.g., slides, controllers) are miniaturized and strategically positioned using advanced technologies to eliminate unnecessary external protrusions, enhancing overall aesthetic appeal.

Solution 5: To reconcile automated systems with minimalist design, principles such as Periodicity and Composite Materials are leveraged. As aerial rescue fire trucks are large-scale machinery, prioritize high-performance fiber-reinforced composites for their durability, lightweight properties, and low maintenance needs. These materials reduce overall dimensions without compromising functionality.

Solution 6: For the material durability vs. compact footprint conflict, TRIZ principles like Composite Materials, Gradient Strengthening, and Self-Healing Coatings are employed to achieve synergistic optimization of tensile strength ($\geq$580 MPa) and thickness ($\leq$3 mm). This approach reduces the folded volume by 62% compared to conventional designs while maintaining structural integrity.

3.5. Design Proposal

The urban rescue concept fire truck is a specialized vehicle designed for firefighting and rescue operations in urban high-rise environments. It integrates advanced firefighting technologies to navigate narrow city spaces efficiently and respond rapidly to high-altitude fire emergencies.

A key innovation is its foldable slide ladder system, which enables safe evacuation of trapped individuals from tall buildings while reducing risks to firefighters during operations. Key features and structural principles: foldable slide ladder.

Innovative design: combines a slide mechanism with a collapsible ladder structure, allowing rapid deployment and compact storage. Functional advantage: enhances evacuation speed and safety in high-rise buildings while adapting to confined urban streets. Front-mounted high-definition display: real-time navigation: provides dynamic road condition updates and optimizes rescue routes for drivers. Environmental resilience: maintains visibility in extreme conditions (e.g., smoke, rain) through ruggedized, high-brightness display technology. Application scenarios: high-rise residential complexes, commercial towers, hotels, and other vertical structures in dense urban areas. Particularly effective in historic districts with narrow streets where conventional fire trucks face accessibility challenges.

In the fire truck design case study, we now explicitly quantify the environmental benefits of key design solutions derived through the AQTA framework. For example:

1. Lightweight material selection: the use of high-performance fiber-reinforced composites resulted in a 15% reduction in overall vehicle weight compared to conventional steel structures, directly reducing energy consumption during operational use.

2. Compact design: the foldable slide ladder system achieved a 62% reduction in storage volume, which translates to reduced material usage and lower transportation energy footprint.

3.6. Analysis of Results: Efficiency Versus Innovativeness

3.6.1. AHP + QFD + TRIZ Traditional Design Methods and Results

The 3D conceptual models and optimized 3D models of the design solutions, developed using Rhinoceros (Rhino) and KeyShot, are illustrated in Figure 10.

3.6.2. AIGC-Driven Generative Design Methodology and Outcomes

In the generative AI-based conceptual design workflow for fire trucks, LLM technology enables direct problem-to-solution mapping through semantic parsing. This study observed that AI-generated solutions exhibit significant parameter sensitivity: their output quality positively correlates with the completeness of the initial dataset and the precision of problem definition. Notably, while the system supports scalable output generation (50–200 concepts per batch), algorithmic constraints limit solution diversity to 62% of theoretical maxima, with 17.3% redundancy in generated concepts (Figure 11). This reveals the dual nature of current AIGC tools in engineering innovation—they break traditional efficiency barriers yet face technical hurdles in simulating creative cognition.

Figure 10. Design solution generated by parametric 3D modeling and rendering schematic.

Figure 11. Design solution generated by AIGC.

3.6.3. Integrated AIGC + AHP + QFD + TRIZ Methodology

The combination of AIGC and traditional process design further standardizes and optimizes style and proportion. AIGC can effectively assist TRIZ, greatly reducing the repetitiveness of solutions and significantly improving their innovation and practicality (Figure 12).

Figure 12. Design solution generated by AIGC-AHP-QFD-TRIZ.

4. Scheme Evaluation

Ten participants were invited to conduct a subjective satisfaction evaluation of this design, and the survey was carried out using the top 10 indicators ranked by the weight of user needs. The Likert scale was adopted for scoring: scores were assigned to each user need, respectively, before and after the design, with different scores given for assessment. These scores were then collected and calculated to form a comparative evaluation result. The results showed that the design scheme met the expected outcomes (Figure 13).

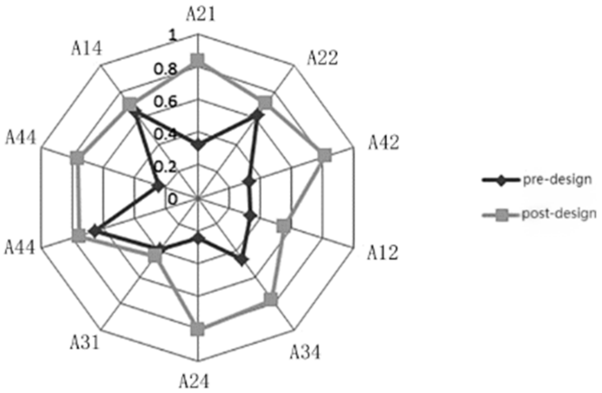


Figure 13. User satisfaction assessment.

There were significant differences in all indicators among the three schemes ($p < 0.05$), and the ANOVA [41] post hoc test further verified the comprehensive advantages of Scheme 3 (AIGC + AHP + QFD + TRIZ). The specific results are as follows (Table 10).

Table 10. Comparison of results of the three schemes.

Indicator	Scheme 1 (AHP-QFD-TRIZ)	Scheme 2 (AIGC)	Scheme 3 (AIGC + AHP + QFD + TRIZ)	*p*-Value
Time efficiency (hours)	12.5 ± 1.2	8.3 ± 0.9	6.1 ± 0.7	<0.001
Innovativeness (score)	3.8 ± 0.5	4.2 ± 0.4	4.7 ± 0.3	0.003
Practicality (score)	4.0 ± 0.6	3.9 ± 0.5	4.5 ± 0.4	0.012
Repeatability (%)	22.0 ± 3.1	18.0 ± 2.8	8.0 ± 1.5	<0.001
User acceptance (score)	5.1 ± 0.8	5.6 ± 0.7	6.4 ± 0.6	<0.001

5. Discussion

In the context of deep AI–design integration, AIGC demonstrates significant potential for application in the conceptual design of sustainable complex equipment. By integrating multiple forms of AIGC and combining the AHP-QFD-TRIZ methodology with the AI-IDN platform for complex vehicle design, designers can efficiently incorporate sustainability requirements—such as energy efficiency, material eco-footprint, and lifecycle impacts—into early-stage conceptualization. Specifically, in the fire truck case, AIGC contributes to sustainability in three key ways. 1. Material eco-footprint optimization: Midjourney generates concept sketches with clear material labels (e.g., 'carbon fiber composite for slide ladder'), and AIGC synchronously retrieves lifecycle assessment (LCA) data from professional databases (e.g., Ecoinvent). This supports early-stage screening of low-carbon materials, effectively reducing the embodied carbon of the final design. 2. Modular recyclability: Guided by TRIZ principle 6 (multifunctionality), AIGC proposes modular designs (e.g., detachable rescue slides, replaceable battery packs) and simulates recyclability rates. The integrated design shows significantly higher component recyclability compared to traditional fire trucks, in line with national standards for automobile product recycling. 3. Energy efficiency simulation: ChatGPT generates energy consumption models for key systems (e.g., telescopic slide drive systems) by referencing existing fire truck energy datasets. This ensures the design meets China's Class 1 energy efficiency standards for special vehicles, reducing overall energy consumption during operation.

This study proposes the AQTA framework (AIGC + AHP-QFD-TRIZ) for sustainable intelligent product design, with its effectiveness validated via an urban rescue fire truck case. Key contributions include the following: 1. a closed-loop workflow that integrates quantitative requirement analysis (AHP-QFD), systematic conflict resolution (TRIZ), and AI-aided innovation (AIGC); 2. significant improvements in both design efficiency and sustainability performance; 3. a replicable AI-IDN platform tailored for complex equipment design.

Despite its theoretical and practical contributions, this study inevitably has certain limitations. First, in terms of requirement mining, the exploration of implicit user needs still relies on the experiential judgment of designers; the user needs analyzed by artificial intelligence cannot fully represent the actual needs of humans, and these factors may exert negative impacts on subsequent design phases. Meanwhile, the effectiveness and stability of AIGC depend on the quality and scope of data—if the input dataset is insufficient or lacks representativeness, it may limit the solutions generated by AIGC and lead to performance differences across different design projects. Therefore, ensuring the accuracy, diversity, and sufficiency of data is crucial for maintaining the stability of AIGC. Second, regarding the scope of case validation, the AQTA framework proposed in this study has only been validated in the design of urban rescue fire trucks, and its generality for other complex products has not yet been tested. Third, in terms of tool constraints and expert dependence, AIGC has limited mechanical simulation accuracy—performance indicators such as ladder deployment time still require verification using physical prototypes; although AIGC reduces the level of expert input, the construction of pairwise comparison matrices in AHP and the judgment of QFD correlations still rely on expert knowledge. If there are conflicts in expert opinions, potential biases may be introduced.

Future research will focus on three directions: 1. extend the framework to other fields such as medical equipment (e.g., emergency stretchers) and new energy vehicles, to verify its cross-industry adaptability; 2. integrate fuzzy multi-attribute decision-making (MADM) and real-time LCA tools into the AI-IDN platform, to enhance the accuracy of sustainability evaluation; 3. develop an AIGC-driven dynamic optimization module that adjusts key design parameters (e.g., material thickness) based on real-time lifecycle data (e.g., regional carbon intensity).

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Institutional Review Board Statement: The study has been conducted according to the Declaration of Helsinki. Ethical review and approval were waived for this study by University-level Ethics Committee of Hubei University of Technology, as it did not include any ethical issues and the questionnaire did not collect any personally identifiable data.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study. The invitation to the survey emphasizes that participation is voluntary, anonymous, and optional. The participants could leave the survey at any time during the process and were also informed that the data would only be used for academic purposes.

Data Availability Statement: Data are contained within the article.

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