Group Decision Making for Product Innovation Based on PZB Model in Fuzzy Environment: A Case from New-Energy Storage Innovation Design

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Abstract: According to the World Economic Forum, countries and regions should steer their energy systems toward cheaper, safer, and more sustainable energy sources, and move away from their reliance on traditional energy sources. With this trend, it is significant that new-energy battery enterprises should not only maintain their current installed product, but also attract more consumers. Due to the differences in customers, there are different requirements for the products. Thus, this paper chooses new-energy storage product innovation design as the object, and proposes a novel multiagent group decision-making method based on QFD and PZB models in a fuzzy environment. Firstly, extensively collected multiagent (consumer and designer) requirements are transformed into specific functions through an extended multiagent QFD with HFLTS, and the relationship coefficients are derived. Afterward, different design schemes for functional components are evaluated according to the concept of the PZB model. Then, the satisfaction degree interval is calculated for each partial design. On the basis of these indicators, a multiagent multi-objective optimization model is established. Afterward, solving he model through NSGA-II quickly generates the most suitable product innovation design scheme. Lastly, the feasibility and superiority of proposed method are illustrated through innovation design for a new-energy storage battery.

Keywords: HFLTS; quality function deployment; service quality gap; PZB model; product innovation; fuzzy linguistic terms

MSC: 90B50; 03E72; 90C27

1. Introduction

In recent years, increasingly serious environmental problems, such as global warming and air pollution, have led to many countries focusing on the development of new energy such as wind and solar energy. There is no doubt that the innovation of new-energy storage batteries is becoming more and more important for promoting new-energy development and application. The innovation of new energy can be divided into two aspects: radical innovation, which is disruptive, and incremental innovation, which is progressive. Both radical innovation and incremental innovation are systemic questions limited by complex factors, such as high technical limitations, manufacturing environment limitations, market recognition limitations, and high continued investment. In view of this, this paper focuses on the incremental innovation of new-energy electromagnetics, i.e., the continuous innovation of new-energy electromagnetics to promote the development of new energy.

The generation of innovation design is the first stage of the product life cycle, which significantly affects later stages, such as manufacture planning and supplier selection. In innovation design, adjustment and innovation based on target requirements can effectively improve the satisfaction with respect to the requirements proposed. Under these complex...
factors, the function that best enhances the product satisfaction degree can be identified from target group, and innovation of this function can be prioritized to significantly improve the competitiveness of the product. Anning-Dorson pointed out that innovation is one of the most meaningful strategies to reduce threat and create opportunities when enterprises are facing uncertain environmental factors, such as product competition and changing customer demands [1]. Lee et al. stated that the customer requirements are crucial for incremental innovation, but sometimes implicit. If the CRs are ignored, incremental innovation will inevitably fail [2]. Thus, product innovation design while fully considering the target agent group requirements is significant to help enterprises to promote competitiveness. The innovation problem has been widely addressed by many scholars. Eum et al. pointed that promotion of techniques is a vital force for innovation [3]. Vos proposed that products with high modularity can successfully respond to customer requirements and promote the sustainable innovation ability of enterprises [4].

Many studies have focused on the innovation of products and services. Many of them paid attention to the innovation of existing products using new energy instead of fossil fuels, whereas fewer studies considered the innovation design of new-energy storage batteries. In addition, the market requirements are also a matter of concern. The existing studies generally only considered customer demands to push product innovation, while ignoring the demand from designers to drive proactive product innovation [5]. Moreover, the traditional evaluation method in innovation is quantitative or simple qualitative with a precise number. This makes it difficult for evaluators to express comprehensive evaluations, rendering this method unsuitable for incremental innovation. When calculating the satisfaction degree of target agent evaluators, current studies preferred to evaluate a single dimension of product performance or service quality evaluation. This hardly reflects the true satisfaction degree of the target groups. In general, there are gaps in the research which need to be addressed. This will allow developing innovation more quickly and efficiently, while comprehensively satisfying the requirements of multiagent groups. Furthermore, the competitiveness and influence of enterprises can be significantly improved. Hence, on the basis of these research gaps, this paper proposes a novel multiagent group decision-making (multi-agent GDM) method for a new-energy household storage battery in a fuzzy environment (FE).

In evaluation processing, various evaluators sometimes differ due to personal preference and knowledge limitations. These evaluations are typically expressed using linguistic terms with uncertainty. Thus, an appropriate method for their aggregation is significant. The hesitant fuzzy linguistic term set (HFLTS) with envelopes proposed by Liao [6,7], based on the study by Rodriguez [8], is suitable for dealing with this situation. Moreover, in the scenario of this paper, the evaluations were collected from multiagent groups, customer groups, and designer groups. Thus, the QFD adjusted for this scenario is suitable when considering two kinds of evaluations from multiagent groups. Furthermore, each evaluation should be considered in two dimensions, expected value and perceived value, instead of the single-dimension evaluation proposed in most studies. To better indicate product innovation, the Parasuraman–Zeithaml–Berry (PZB) model of service quality gaps proposes a perceived interval indicator of both evaluation dimensions to present the inner satisfaction degree of evaluators [9,10]. Consequently, on the basis of the core concepts of the above methods, the proposed method can help enterprises to generate more competitive product innovation design.

The main contributions of this paper are divided into three points:

This paper considers multiagent group requirement for product innovation. Specifically, innovation is determined by not only market demand but also technical improvement and upgrading practice. However, traditional product innovation design only considers customer demands and ignores designer demands. Thus, we consider many factors (demand-driven and technology-driven) and collect them through multiagent group requirements (market customers and enterprise designers).
This paper considers two evaluation dimensions, the expected value and the perceived value, instead of only one dimension. Furthermore, according to the core concept of PZB model, the variance of these two values can better reflect the real satisfaction of multiagent groups, which means that the innovation design through this proposed method is more effective in improving the satisfaction degree of target groups.

This paper combines the adjusted QFD, the PZB model, and the HFLTS with envelopes to comprehensively analyze the multiagent GDM question for innovation design. The combination of multiagent QFD and HFLTS with envelopes can more comprehensively transform the requirements from multiagent groups into product functional components (FCs) for multiagent GDM. Coupled with the theory of the PZB model, this combination is more suitable to solve the multiagent GDM question for innovation design.

The proposed method considers not only the demands of key customers but also the demands of other customers and enterprise designers. These demands are processed using QFD with HFLTS. Furthermore, the evaluation of partial designs for each functional component is based on the PZB model and HFLTS. In this case, the proposed method can more comprehensively consider the requirements and significantly reduce the loss of linguistic information, as well as truly reflect the inner satisfaction of multiagent groups. Accordingly, the method can quickly and effectively generate innovative designs to improve the competitiveness of a product. A case study on XX company’s new-energy storage battery is used to validate the above advantages.

This method, therefore, takes into account the need for a more comprehensive approach while reducing the loss of linguistic information, and it provides a more realistic picture of the inner real satisfaction of key groups with the product. Accordingly, the method can quickly and effectively generate innovative designs for more competitive products.

The remaining sections of this paper are organized as follows: Section 2 presents a review of the literature. A description of the research question is provided in Section 3, while the methodology is presented in Section 4. Lastly, a case study is presented in Section 5, and the work is concluded in Section 6.

2. Literature Review

The extent to which the functional performance of product meets the requirements of the target people, i.e., the satisfaction degree, is a key factor when presenting the feasibility and quality of product innovation. Meanwhile, its use to guide innovation design is typically a complex decision-making (DM) question for innovation design groups. For different innovation scenarios, studies have extended the question to multicriteria decision making (MCDM), multicriteria group decision making (MCGDM), and multi-perspective multi-attribute decision making (MPMADM), proposing different ways to deal with these scenarios.

In reality, fuzzy sets are generally considered in the DM question for innovation. Specifically, the innovation environment is typically uncertain, and the information from customers or other key contributors to innovation is vague [11]. In this case, to solve the MCDM question, Pamucar’s study introduced the fuzzy number into the best–worst model (BWM) and iterative multicriteria decision making (TODIM) method to consider information with uncertainties [12], thereby helping the development of solutions for zero-carbon transport in London [12]. In Poorkavoos’s study, fuzzy sets were combined with qualitative analysis for fuzzy sets qualitative comparative analysis [13], and then applied to identify the suitable configuration of innovation pathways for small and medium-size enterprises (SMEs), i.e., solving the MCDM of allocating disruptive and incremental innovation inputs [13]. During the past few decades, intuitionistic fuzzy sets (IFSs) were proven to better present imprecision and fuzziness than ordinary fuzzy sets. Recently, Ren’s study used the IFS combined with the thermodynamic method to propose a new MCDM method, which was applied to improve the processing ability of the classified medical system in a Chinese hospital [14]. Shen extended the IFS sorting method to take
account of solving group decision-making (GDM) questions and to develop an adaptive search and adjustment method for group consensus [15]. In recent decades, many studies agreed that the hesitant fuzzy linguistic term set (HFLTS) can present more comprehensive information with uncertainties. Wu et al. proposed a consensus measure approach based on HFLTS aggregation operators and possibility distributions to support stakeholders making rational decisions [16]. Chen’s study used a two-stage aggregation paradigm for computing HFLTS possibility distributions, considering both environmental and social sustainability to establish a multi-perspective multi-attribute decision-making (MPMADM) framework [17] that can offer systematic decision support for enterprises to select the optimal third-party reverse logistics provider [17]. Yavuz introduced the analytic hierarchy process (AHP) and HFLTS into fuzzy decision making to solve the alternative-fuel vehicle selection problem of a home healthcare service provider in the USA [18]. Adem’s study utilized AHP and HFLTS as an MCDM approach to calculate the weights of green ergonomics framework principles, allowing the most critical principle to be easily determined to guide enterprise development of green ergonomics [19].

Recently, the QFD has been widely accepted to deal with product design and quality innovation. For innovation processing, Liao et al. pointed out that customer demands have a positive moderating effect in promoting enterprise innovation ability and innovation intensity through the analysis of 2156 manufacturing companies [20]. Zhang et al. proposed an innovation design solving approach based on quality function deployment (QFD), the theory of innovation problem solving (TRIZ), and fuzzy decision-making theory to deal with customer demands and develop ergonomic product innovation design [21]. Awanis Romli et al. stated that the life cycle assessment (LCA) theory can be combined with QFD to help enterprises develop eco-design GDM of product innovation, using the eco-redesign of a single-use medical forceps as a case study [22]. Liu applied interval-valued intuitionistic fuzzy sets (IVIFS) and the technique for order performance by similarity to an ideal solution (TOPSIS) in multi-attribute group decision making (MAGDM) to effectively reveal the opinions of top management [23]. Lee’s study proposed that, by carefully considering the voices of customers, the combination of ontology-based design knowledge hierarchy (DKH), TRIZ, and the QFD can provide an effective approach to generate practical and competitive digital technology innovation [2]. However, some scholars suggested that innovation should consider key roles beyond customers. Yu’s study stated that innovation needs to consider both customer demands from the market and designer demands from the enterprise according to technical and technological factors [5]. Çevik Onar incorporated HFLTS into quality function deployment (QFD) to consider both customer requirements and product workstation design requirements for the GDM question with regard to computer workstation selection [24]. Zhan et al. set up a model to assess the interaction between satisfaction of customer requirements (CRs) and fulfillment of design requirements (DRs) to generate the most suitable new product planning method for enterprises [25]. This model was established as a function of the evaluated relationship between customer requirements (CRs) and design requirements (DRs) during QFD and the self-correlation of DRs [25]. For the different service preferences of enterprises, such as supplier priority and customer priority, Vezzetti proposed a 3D-QFD model that collects evaluations from two customers and one supplier or two suppliers and one customer [26]. The 3D-QFD model could better present the relationship between stakeholders and cope with more complex scenarios [26]. When the customers’ voices and the designers’ propositions are both considered in product innovation, the evaluation and transformation of requirements are naturally different.

When collecting evaluations of quality innovation development, some studies focused on the evaluation dimensions to better present the true inner thoughts of demand proposers. Lemon believed that, to understand customers, the customer experience, customer journey, and the experience management require further consideration [27]. Specially, the expectations and the perceptions of services or products are significant for evaluating the customer experience [27]. Xu’s study stated that the gap between the expected evaluation and the perceived evaluation, as proposed by Parasuraman et al., is an essential indicator
for guiding service companies to improve their service quality [9,10,28]. Behdioğlu’s study applied fuzzy sets and the expectation–perception gap of the Parasuraman–Zeithaml–Berry (PZB) service quality model to evaluate and improve the service quality of a hospital in Turkey [10,28]. Tan et al. combined the theory of the PZB model and the technology acceptance model (TAM) to propose an innovation design approach that meets customers’ demands and maximizes their satisfaction [29]. This approach was used for the innovation design and examination of an online language learning system [29].

The recent studies on decision making with respect to innovation are analyzed in Table 1.

Table 1. Recent studies about innovation.

| Reference | Question Type | Method for Uncertain Scenario | Evaluation Dimension | Problems |
|-----------|---------------|-------------------------------|----------------------|----------|
|           | Single Agent  | Multi Agent                  | Complex              |          |
|           |               | Ordinarily Fuzzy Sets         | Intuitionistic       |          |
|           |               |                               | Fuzzy Sets           |          |
|           |               |                               | Hesitant Fuzzy Set   |          |
|           |               |                               | Others               |          |
| [2]       | √             | √                             | √                    |          |
|           |               |                               |                      | How to generate practical and competitive computer-aided innovation |
| [12]      | √             |                               | √                    |          |
|           |               |                               |                      | The environmental uncertainties of zero-carbon transport development |
| [13]      | √             |                               | √                    |          |
|           |               |                               |                      | How to allocate resources into innovation pathway for SMEs |
| [14]      |               | √                             | √                    |          |
|           |               |                               |                      | How to improve the processing ability of a hospital service |
| [15]      | √             |                               | √                    |          |
|           |               |                               |                      | Adaptive search and adjustment approach for group consensus |
| [16]      | √             |                               | √                    |          |
|           |               |                               |                      | Consensus measure approach |
| [17]      | √             |                               | √                    |          |
|           |               |                               |                      | How to select third-party logistics provider for cycle economy |
| [18]      | √             |                               | √                    |          |
|           |               |                               |                      | Selection of alternative solution in operation innovation |
| [19]      | √             |                               | √                    |          |
|           |               |                               |                      | Calculation of MCDM for green ergonomic innovation |
| [21]      | √             |                               | √                    |          |
|           |               |                               |                      | Ergonomic product design based on customer demands |
| [22]      | √             |                               | √                    |          |
|           |               |                               |                      | Eco-design for product innovation |
| [24]      | √             |                               | √                    |          |
|           |               |                               |                      | How to both consider customer demands and workstation design demands |
| [25]      | √             |                               | √                    |          |
|           |               |                               |                      | Interaction between satisfaction of customer demand and fulfillment of enterprise designer |
| [26]      | √             |                               | √                    |          |
|           |               |                               |                      | Innovation design with different preferences based on customer demand and enterprise demand |
| [28]      | √             |                               | √                    |          |
|           |               |                               |                      | Improving quality innovation based on service quality gap |
| [29]      | √             |                               | √                    |          |
|           |               |                               |                      | Customer satisfaction according to evaluation variance between expectation and perception |
| [30]      | √             |                               | √                    |          |
|           |               |                               |                      | Innovation design for online learning system based on customer demand |

According to Table 1, the following conclusions can be drawn:

1. The existing decision-making studies about quality innovation generally considered the uncertainties for real-life scenarios. Many scholars agreed that the group decision-
making (GDM) method allows for a more comprehensive collection and consideration of the requirements of crucial target people. It can be applied to address many meaningful innovation questions, such as product development, service improvement, and selection of alternative options in operation innovation. Thus, this paper chooses the GDM approach to solve the innovation question.

2. Although many studies aggregated several decision makers as the evaluators for quality innovation, they still only paid attention to the voices of customers. In fact, innovation design should consider not only customer demands but also the demands of other crucial people, such as the manufacture limitations and upgraded technologies of design engineers. Thus, this study aggregates customers into a market agent group as a decision maker and aggregates designers into an enterprise agent group as another decision maker. Then, the generated multiagent group decision-making (multi-agent GDM) method based on extended QFD is used to widely collect and comprehensively analyze the evaluations of crucial target people.

3. For dealing with uncertainties, ordinary fuzzy sets and intuitionistic fuzzy sets are widely applied to reduce the loss of information due to uncertainties. However, the HFLTS with envelopes is more suitable for multiagent GDM, because the aggregation of HFLTS can maintain more vague linguistic information in further calculations. In this study, the HFLTS with envelopes is used to improve the applicability of the model. Hence, the proposed method also applies the HFLTS to deal with the vagueness of linguistic information.

4. Evaluation processing is the foundation of innovation, but most studies focused on a single dimension to present the satisfaction of customers. Practically, the service quality gap is more appropriate to express people’s true inner satisfaction with a product or service. Hence, this paper chooses the satisfaction variance between the expected value and perceived value according to the theory of the PZB model for the evaluation process of the proposed method.

3. Question Description

This paper proposes a novel multiagent group decision-making (multi-agent GDM) method for product innovation design in a fuzzy environment, in order to promote the product to better meet multiagent requirements. According to Yu’s study, product innovation is affected by two main aspects, demand-driven and technology-driven factors [5]. These two factors are represented as customer requirements (CR) from the market and design engineering requirements (DR) from the enterprise. Xu’s study pointed out that the difference between performance expectation and performance perception is more suitable for the improvement of products or services [30]. On the basis of this difference, the satisfaction degree interval of a product can be obtained through complex calculation. A smaller interval indicates that the product can better satisfy multiagent requirements. In addition, it should be noted that evaluators may use words with uncertainty, such as “not too bad” or “fine”, instead of precise scores to more comprehensively express their personal preference, knowledge limits, complex environment, etc. [8,31] Comprehensively, the satisfaction of multiagent requirements can be maximized, only when the intervals with vague linguistic information are minimized.

Specifically, the proposed method can be divided into five steps:

1. In the process of innovation, two agent groups based on market demand and enterprise demand are considered to take account into the demand-driven and the technology-driven factors.

2. In evaluation, HFLTS is introduced to collect evaluation information according to personal preference, knowledge limitation, evaluation environment, etc., so that evaluators can better express their comprehensive evaluation with less loss of vague linguistic information. In further steps, the transformation from HFLTS with envelopes to the trapezoidal fuzzy number is introduced.

3. Then, the QFD based on the multiagent group and fuzzy linguistic evaluation is introduced, so that the requirements from the multiagent group can be more compre-
hensively converted into product functional components (FCs). In this step, the relative weights of each FC are obtained for further calculations.

4. Next, as evaluation indicators, two aspects of evaluation, performance expectation and performance perception, are considered. Then, the satisfaction degree is obtained in terms of two aspects, expected value and perceive value. On the basis of the PZB model, the interval of the two values can more effectively guide innovation to satisfy target groups.

5. Lastly, the adjusted QFD and PZB models are combined to establish a multi-agent multi-object optimization model for generating the ideal innovation design scheme. The NSGA-II algorithm is applied to quickly generate the most suitable scheme.

To easily understand the proposed method, its structure is shown in Figure 1. After a description of the overall proposed method in Section 4, innovation design for a low-carbon new-energy household storage battery is chosen as a case study to illustrate the feasibility and practicality of the proposed method in Section 5.

Figure 1. The structure of the proposed multiagent GDM method for product innovation design.

The following symbols are employed for convenience:

$$IDG = \{CG, EG\}$$ represents the whole innovation design group, which consists of industry experts, where $CG$ presents the market subgroup, and $EG$ presents the enterprise subgroup;

$$CR = \{CR_1, CR_2, \ldots, CR_n\}$$ represents the customer requirements, where $CR_j$ denotes the $j$-th customer requirement, $j = 1, 2, \ldots, n$;

$$DR = \{DR_1, DR_2, \ldots, DR_g\}$$ represents the design engineering requirements, where $DR_k$ denotes the $k$-th enterprise design engineering requirement, $k = 1, 2, \ldots, g$;

$$D = \{D_1, D_2, \ldots, D_m\}$$ represents the functional components of the product, where $D_i$ denotes the $i$-th functional component, $i = 1, 2, \ldots, m$;

$$D_{ij} = \{D_{i1}, D_{i2}, \ldots, D_{im}\}$$ represents the $i$-th functional component, where $D_{ij}$ denotes the $j$-th partial design scheme of the $i$-th functional component, $j = 1, 2, \ldots, m$;

$s_{ij}$ describes the self-correlation of functional components, which can be congregated into $S = [s_{ij}]_{m \times m}$ as the self-correlation part of the multi-matrix;

$r_{ij}$ describes the relationship of functional components with the requirements from customers, which can be congregated into $R = [r_{ij}]_{n \times m}$ as the market relevance part of the multi-matrix;

$t_{ij}$ describes the relationship of functional components with the requirements from designers and engineers, which can be congregated into $T = [t_{ij}]_{g \times m}$ as the enterprise relevance part of the multi-matrix;
\[ p = \{p_{11}, p_{12}, \ldots, p_{1p}, \ldots, p_{21}, \ldots, p_{2p}, \ldots, p_{ip}, \ldots, p_{ip} \} \], \text{ where } p_{ip} \text{ denotes the enterprise providing ability of the partial design scheme } D_{ij}, \text{ evaluated by the whole innovation design group;}

\[ q = \{q_{11}, q_{12}, \ldots, q_{1q}, q_{21}, \ldots, q_{2q}, \ldots, q_{iq}, \ldots, q_{ip} \}, \text{ where } q_{ip} \text{ denotes the functional performance of the partial design scheme } D_{ij}, \text{ evaluated by the whole innovation design group;}

\[ u = \{u_{11}, u_{12}, \ldots, u_{1u}, u_{21}, \ldots, u_{2u}, \ldots, u_{iu}, \ldots, u_{ip} \}, \text{ where } u_{ip} \text{ denotes the synthesis functional performance of functional component } D_i \text{ produced by the enterprise through partial design scheme } D_{ij}, \text{ and } Q(u_{ip}) \text{ denotes the satisfaction degree of functional component } D_i \text{ through partial design scheme } D_{ij} \text{ to multiagent group.}

\section*{4. The Proposed Method}

\subsection*{4.1. Mathematical Process of Fuzzy Environment}

\subsection*{4.1.1. HFLTS and Context-Free Grammar}

The HFLTS adjusted by Liao’s study is significant for decision makers to deal with product innovation design [6]. Other practical questions consider evaluations from the target agent group. In fact, most customers struggle to use numerical information and certain descriptions for evaluation. Most experts prefer to use complex descriptions with uncertainties rather than precise numbers or single and simple linguistic terms, because they cannot fully express their complete and true evaluation [31]. For these reasons, Rodriguez proposed hesitant fuzzy linguistic term sets (HFLTS) with ordered and coherent linguistic term sets, which is more suitable for evaluation than traditional fuzzy linguistic term sets [8]. However, Rodriguez did not present a specific mathematical concept of HFLTS, and the HFLTS is based on an asymmetric continuous language evaluation criterion. Thus, it may present some anomalies in some calculation circumstances. In this case, Liao et al. redefined HFLTS using symmetric and continuous evaluation criteria, and proposed a mathematical form for a generic set of hesitant fuzzy language terms, named hesitant fuzzy linguistic elements (HFLE) for convenience [6,7]. Thus, HFLTS can play a key role in product innovation to accurately describe the evaluation of most people with no loss of information.

**Definition 1 ([32]).** There is a subscript of a symmetric and continuous set of assessment language terms \( S = \{s_i|l = -\tau, \ldots, 0, 1, \ldots, \tau\} \), where the central number “0” denotes an “undifferentiated” assessment value, and the remaining scales are symmetrically distributed on either side; \( s_{-\tau} \) and \( s_{\tau} \) are the upper and lower bounds of the language scale, respectively, and \( \tau \) is a positive integer. Furthermore, \( x_i \in X(i = 1, 2, \ldots, N) \), where the HFLTS mathematical form of \( X \) is \( H_S \), expressed as \( H_S = \{s_i, h_i(x_i)|x_i \in X\} \). The function \( h_i(x_i): X \rightarrow S \) represents the possible degree of membership of \( x_i \in X \) mapping to \( A \subset X \), where \( h_s(x_i) = \{s_{\varphi 1}(x_i), s_{\varphi 2}(x_i), s_1, s_2, \ldots, L\} \) is a row of possible values in the set of linguistic terms \( S \), where \( L \) is the number of linguistic terms of \( h_s(x_i) \), and \( \varphi 1 \in (-\tau, \ldots, -1, 0, 1, \ldots, \tau) \) is the subscript of linguistic term \( s_{\varphi 1}(x_i) \). For convenience, \( h_s(x_i) \) is considered a hesitant fuzzy linguistic element (HFLE).

\( S \) should satisfy the following conditions: if \( \alpha > \beta, s_\alpha < s_\beta, neg(s_\alpha) = s_{-\alpha}, \) and \( neg(s_0) = s_0 \).

The semantics of the seven-rank subscript symmetric language term set are shown in Figure 2.

The basic calculation rule is as follows:

- The complementary: \( H_S^c = S - H = \{s_i|s_i \in S \text{ and } s_i \notin H\} \};

- The union: \( H_S^1 \cup H_S^2 = \{s_i|s_i \in H_S^1 \text{ or } s_i \in H_S^2\} \), denoted by \( H_S^{1,2} \);

- The intersection: \( H_S^1 \cap H_S^2 = \{s_i|s_i \in H_S^1 \text{ or } s_i \in H_S^2\} \), denoted by \( H_S^{1,2} \).

**Definition 2 ([8,33]).** Consider a linguistic term set \( S \). Let \( G_H \) be the context-free grammar, which can be defined as \( G_H = (V_N, V_T, I, P) \), where \( V_N \) is the set of non-terminal symbols, \( V_T \) is the set of terminal symbols, \( I \) is the starting symbol, and \( P \) denotes the production rules, which are defined in an extended Backus–Naur form [33]. Among the terminal symbols of \( G \), the primary terms
low, medium, or high), hedges (e.g., not, much, or very), relations (e.g., lower than or higher than), conjunctions (e.g., and or but), and dis--functions (e.g., or) can be found. Thus, choosing I as any non--terminal symbol and using P can generate linguistic expressions such as lower than medium or greater than high.

Figure 2. The seven--rank subscript symmetric language term set.

Definition 3 ([8,34,35]). Let \( E_{GH} \) be the function which transforms the linguistic expressions \( l \in S_H \) generated by context-free grammar \( G_H \) into a set of hesitant fuzzy linguistic terms \( H_S \). Let \( S \) be the linguistic term set for \( G_H \), and \( S_H \) be the set of all expressions generated by \( G_H \). Accordingly, \( E_{GH} : S_H \to H_S \) can be described by the following formulas:

\[
E_{GH}(s_i) = \{ s_i | s_i \in S \};
\]

\[
E_{GH}(\text{at most } s_i) = \{ s_i | s_i \in S \text{ and } s_i \leq s_i \};
\]

\[
E_{GH}(\text{lower than } s_i) = \{ s_i | s_i \in S \text{ and } s_i < s_i \};
\]

\[
E_{GH}(\text{at least } s_i) = \{ s_i | s_i \in S \text{ and } s_i \geq s_i \};
\]

\[
E_{GH}(\text{greater than } s_i) = \{ s_i | s_i \in S \text{ and } s_i > s_i \};
\]

\[
E_{GH}(\text{between } s_i \text{ and } s_j) = \{ s_i | s_i \in S \text{ and } s_i \leq s_i \leq s_j \}.
\]

The transformation process is shown in Figure 3.

Figure 3. The translating process from evaluation to HFLTS using context-free grammar.

Definition 4 ([8]). The upper and the lower bounds of HFLTS can be defined as follows:

\[
H_S^+ = \max(s_i) = s_j, s_j \in H_S, \text{ and } s_i \leq s_j, \forall j.
\]

\[
H_S^- = \min(s_i) = s_j, s_j \in H_S, \text{ and } s_i \geq s_j, \forall j.
\]

Definition 5 ([36]). The envelope of HFLTS is named env\((H_S)\) for convenience, which is an interval limited by the upper bound \(H_S^+\) and the lower bound \(H_S^-\). Thus, it can be described through env\((H_S) = [H_S^-, H_S^+]\), \(H_S^- < H_S^+\).

An example is presented below to explain Definition 4 and Definition 5.

Example 1. Consider a linguistic term set \( S = \{ s_0 : \text{very low}, s_1 : \text{low}, s_2 : \text{slight low}, s_3 : \text{medium}, s_4 : \text{slight high}, s_5 : \text{high}, s_6 : \text{very high} \} \) and an HFLTS \( H_S(U) = \{ s_3 : \text{medium}, s_4 : \text{slight high}, \)
4.1.2. Hesitant Fuzzy Number for HFLTS with Envelope

Although context-free grammar can transform linguistic information into HFLTS, it should still be converted into a fuzzy number for further calculation. In this paper, considering the universality of the method, the trapezoidal fuzzy number was deemed more suitable for HFLTS. For the envelope of HFLTS, \( \text{env}(H_S) \), there are \( H_S^- = s_l, H_S^+ = s_m \), and \( s_l, s_m \in H_S \). Hence, the expression of \( \text{env}(H_S) \) can be generated using the trapezoidal fuzzy number as follows [28,37]:

\[
\bar{s}_{lm} = s^1_{lm}, s^2_{lm}, s^3_{lm}, s^4_{lm} = \left( \max \left\{ \frac{2l - 1}{2T + 1}, 0 \right\}, \frac{2l}{2T + 1}, \frac{2m + 1}{2T + 1}, \min \left\{ \frac{2m + 1}{2T + 1}, 1 \right\} \right).
\]

(1)

In Dawes’s study, the seven-rank scale was deemed more suitable for the linguistic term set (LTS), because it can maintain the accuracy of evaluation while significantly reducing workload [38]. Using Equation (1), the linguistic terms can be converted into trapezoidal fuzzy numbers, as shown in Table 2.

### Table 2. Seven-rank linguistic term scale for converting to trapezoidal fuzzy number.

| Seven-Rank Linguistic Term Scale | Trapezoidal Fuzzy Number |
|---------------------------------|--------------------------|
| (TU) totally unrelated / (VB) very bad | \( (0, 0, 0.077, 0.154) \) |
| (WR) weakly related / (B) bad | \( (0.077, 0.154, 0.231, 0.308) \) |
| (SWR) slightly weakly related / (SB) slightly bad | \( (0.231, 0.308, 0.385, 0.462) \) |
| (NR) normally related / (M) medium | \( (0.385, 0.462, 0.538, 0.615) \) |
| (SSR) slightly strongly related / (SG) slightly good | \( (0.538, 0.615, 0.692, 0.769) \) |
| (SR) strongly related / (G) good | \( (0.692, 0.769, 0.846, 0.923) \) |
| (TR) totally related / (P) perfect | \( (0.846, 0.923, 1, 1) \) |

In this proposed method, the envelope of HFLTS presents the aggregation of evaluation. An example is presented below.

**Example 2.** Consider a linguistic term set \( S = \{ s_0 : \text{verylow}, s_1 : \text{low}, s_2 : \text{slightlow}, s_3 : \text{medium}, s_4 : \text{slightlyhigh}, s_5 : \text{high}, s_6 : \text{veryhigh} \} \). Expert 1 from the market evaluation group evaluates the relationships between two functional components of Product 1 and customer requirement CR1: \( A = \{ s_0, s_1 \} \) and \( B = \{ s_3, s_4, s_5 \} \), respectively, where \( A \) and \( B \) are the subscript sets of HFLTS. Thus, \( \text{env}(A) = [s_0, s_1] \) and \( \text{env}(B) = [s_3, s_5] \) can be generated, which can be expressed using trapezoidal fuzzy numbers as follows:

\[
\text{env}(A) = [s_0, s_1] = [(0, 0, 0.077, 0.154), (0.077, 0.154, 0.231, 0.308)] = (0, 0, 0.231, 0.308).
\]

\[
\text{env}(B) = [s_3, s_5] = [(0.385, 0.462, 0.538, 0.615), (0.692, 0.765, 0.846, 0.923)]
\]

\[
= (0.385, 0.462, 0.846, 0.923)
\]

In this paper, most evaluations are expressed using HFLTS to maintain the vagueness of information. The evaluations in this method are achieved through the innovation design group (IDG).

4.2. Mapping between Multiagent Requirements and FCs

4.2.1. QFD for Multiagent Requirements

According to Rosnani’s study, the QFD can not only help enterprises to improve the manufacture of a product, but also guide the innovation of product design [39]. For product innovation, the QFD provides a method to convert customer requirements into engineering specifications of a product [40]. Practically, product innovation should consider not only the requirements of customers, which represent the market demands, but also the requirements...
of product designers, which represent the enterprise demands. This is because designers can generally identify significant requirements that the customer ignored.

Yu’s study proposed that product innovation is driven by two aspects, demand-driven and the technology-driven factors [5]. Okan Duru’s study proposed a 3D multilayer QFD design response considering both customers and service providers to avoid focusing too much on the voice of the customer [41].

On the basis of these studies, this paper adjusts the QFD from focusing on the customer requirements to considering multiagent requirements (market customer requirements and enterprise design engineering requirements).

Furthermore, to reduce the loss of linguistic information, the evaluation should be collected using a linguistic approach, represented by fuzzy numbers and QFD to map the requirements to FCs. Specifically, the requirements should be collected from customers and design engineers. Then, some nonuniversal requirements can be introduced according to personal preference. Therefore, four rounds of the Delphi method should be applied to eliminate nonuniversal requirements and generate the crucial multiagent requirement list. In addition, Chaudhuri pointed out that requirements can be transformed into the engineering or technical characteristics of product innovation using HoQ, which is a significant tool of QFD for building a decision matrix [42,43]. In the scenario of this paper, the transformation was based on mapping multiagent requirements to each FCs. Therefore, the map is not a one-to-one correspondence, as one FC may satisfy several multiagent requirements, while one requirement may be satisfied by several FCs. Thus, the self-correlation of functional components is crucial in establishing an HoQ framework.

In this case, the traditional HoQ framework was extended into a multi-matrix framework for the proposed method, as shown in Figure 4.

![Figure 4. The extended HoQ framework for the proposed method.](image-url)
According to the mapping, the self-correlation of FCs and the relationship between FCs and the multiagent requirements can be filled into the multi-matrix of the HoQ, as shown in Figure 5.

Figure 5. The filled HoQ framework for the proposed method.

4.2.2. Relationship between FCs and Multiagent Requirements

After establishing the fuzzy HoQ framework, the relevance of the FC and DR need be evaluated for the enterprise subgroup, the relevance of the FC and CR need be evaluated for the market subgroup, and the self-correlation of FCs needs be evaluated for the whole innovation design group. Then, these linguistic evaluations can be transformed into the HFLE according to Definitions 4 and 5 and Table 2, and then filled into the HoQ as correlation coefficients of the multi-matrix. Because the multi-matrix is a fuzzy matrix, the fuzzy property needs be retained in the whole method.

The coefficients $s_{ij}$ in the self-correlation part of multi-matrix $S$ denote the relationship between functional component $D_i$ and functional component $D_j$. Because it is a trapezoidal fuzzy number, $s_{ij} = (s_{1i}^j, s_{2i}^j, s_{3i}^j, s_{4i}^j)$, $S$ should be expressed as

$$S = \begin{bmatrix}
(s_{11}^1, s_{11}^2, s_{11}^3, s_{11}^4) & (s_{12}^1, s_{12}^2, s_{12}^3, s_{12}^4) & \cdots & (s_{1m_r}^1, s_{1m_r}^2, s_{1m_r}^3, s_{1m_r}^4) \\
(s_{21}^1, s_{21}^2, s_{21}^3, s_{21}^4) & (s_{22}^1, s_{22}^2, s_{22}^3, s_{22}^4) & \cdots & \vdots \\
\vdots & \vdots & \ddots & \vdots \\
(s_{m_1}^1, s_{m_1}^2, s_{m_1}^3, s_{m_1}^4) & (s_{m_2}^1, s_{m_2}^2, s_{m_2}^3, s_{m_2}^4) & \cdots & (s_{m_m_r}^1, s_{m_m_r}^2, s_{m_m_r}^3, s_{m_m_r}^4)
\end{bmatrix}.$$  (2)
\[ R = \begin{bmatrix}
(r_{111}^2, r_{112}^3, r_{112}^4) & (r_{122}^2, r_{122}^3, r_{122}^4) & \cdots & (r_{1m1}^2, r_{1m1}^3, r_{1m1}^4) \\
(r_{211}^2, r_{212}^3, r_{212}^4) & \ddots & \vdots & \vdots \\
(r_{n11}^2, r_{n11}^3, r_{n11}^4) & r_{n2r}^3 & r_{n2r}^4 & \vdots \\
(r_{n12}^2, r_{n12}^3, r_{n12}^4) & \cdots & r_{n4r}^4 & \vdots \\
\end{bmatrix} \]

\[ T = \begin{bmatrix}
(t_{111}^2, t_{112}^3, t_{112}^4) & (t_{122}^2, t_{122}^3, t_{122}^4) & \cdots & (t_{1m1}^2, t_{1m1}^3, t_{1m1}^4) \\
(t_{211}^2, t_{212}^3, t_{212}^4) & \ddots & \vdots & \vdots \\
(t_{n11}^2, t_{n11}^3, t_{n11}^4) & r_{n2r}^3 & r_{n2r}^4 & \vdots \\
(t_{n12}^2, t_{n12}^3, t_{n12}^4) & \cdots & r_{n4r}^4 & \vdots \\
\end{bmatrix} \]

For convenience with regard to the subsequent complex calculation, \( s_{il} = (s_{il}^1, s_{il}^2, s_{il}^3, s_{il}^4) \)
and \( r_{ji} = (r_{ji}^1, r_{ji}^2, r_{ji}^3, r_{ji}^4) \), and \( t_{ki} = (t_{ki}^1, t_{ki}^2, t_{ki}^3, t_{ki}^4) \) can be normalized as follows:

\[ s_{il} = \left( \frac{1}{m} \sum_{i=1}^{m} s_{il}^1, \frac{1}{m} \sum_{i=1}^{m} s_{il}^2, \frac{1}{m} \sum_{i=1}^{m} s_{il}^3, \frac{1}{m} \sum_{i=1}^{m} s_{il}^4 \right) \]

\[ r_{ji} = \left( \frac{1}{m} \sum_{i=1}^{m} r_{ji}^1, \frac{1}{m} \sum_{i=1}^{m} r_{ji}^2, \frac{1}{m} \sum_{i=1}^{m} r_{ji}^3, \frac{1}{m} \sum_{i=1}^{m} r_{ji}^4 \right) \]

\[ t_{ki} = \left( \frac{1}{m} \sum_{i=1}^{m} t_{ki}^1, \frac{1}{m} \sum_{i=1}^{m} t_{ki}^2, \frac{1}{m} \sum_{i=1}^{m} t_{ki}^3, \frac{1}{m} \sum_{i=1}^{m} t_{ki}^4 \right) \]

Consequently, each part of the multi-matrix, \( S = [s_{il}]_{m \times m} \), \( R = [r_{ji}]_{n \times m} \), and \( T = [t_{ki}]_{g \times m} \) can also be normalized.

4.2.3. Relative Weights of FCs

In fact, each FC contributes differently to the performance of the overall product, and each requirement of each agent group plays a different role in the overall innovation design. Hence, these differences have to be taken into account by calculating the relative weight given to the contribution of each FC to each multiagent requirement. The first step for this aim is to determine the absolute weights of CR and DK given by the innovation design group.

\( W = (w_1, w_2, \ldots, w_n) \) is the weight vector for customer requirements, where \( w_j \) denotes the weights or importance of the \( j \)-th customer requirement \( CR_j, j = 1, 2, \ldots, n \).

\( V = (v_1, v_2, \ldots, v_g) \) is the weight vector for design engineering requirements, where \( v_k \) denotes the weights or importance of the \( k \)-th design engineering requirements \( ER_k, k = 1, 2, \ldots, g \).
Furthermore, \( z_i = (z_1, z_2, \cdots, z_m) \) is employed as the absolute weight vector for FCs. It is calculated for each agent group for the scenario in this study.

\[
\begin{align*}
& z_i = \{z_1^a, z_2^b\}, \\
& z_i^a = \sum_{k=1}^n v_k \sum_{i=1}^m \tilde{z}_{il} \otimes \tilde{p}_{ij}, \\
& z_i^b = \sum_{k=1}^n v_k \sum_{i=1}^m \tilde{z}_{il} \otimes \tilde{t}_{ki}.
\end{align*}
\]

where \( z_i^a \) denotes the absolute weight of the FC for customer requirements, which is calculated as follows:

\[
\begin{align*}
& z_i^a = \sum_{k=1}^n v_k \sum_{i=1}^m \tilde{z}_{il} \otimes (\tilde{p}_1^{i}, \tilde{p}_2^{i}, \tilde{p}_3^{i}, \tilde{p}_4^{i}), \\
& z_i^b = \sum_{k=1}^n v_k \sum_{i=1}^m \tilde{z}_{il} \otimes (\tilde{t}_1^{i}, \tilde{t}_2^{i}, \tilde{t}_3^{i}, \tilde{t}_4^{i}).
\end{align*}
\]

In this paper’s scenario, \( z_i \) is converted using the hesitant fuzzy transformation.

\[
\begin{align*}
& \tilde{z}_i^a = \left( \begin{array}{cccc}
\frac{z_1^a}{\sum_{i=1}^m z_i^a}, & \frac{z_2^a}{\sum_{i=1}^m z_i^a}, & \frac{z_3^a}{\sum_{i=1}^m z_i^a}, & \frac{z_4^a}{\sum_{i=1}^m z_i^a}
\end{array} \right), \\
& \tilde{z}_i^b = \left( \begin{array}{cccc}
\frac{z_1^b}{\sum_{i=1}^m z_i^b}, & \frac{z_2^b}{\sum_{i=1}^m z_i^b}, & \frac{z_3^b}{\sum_{i=1}^m z_i^b}, & \frac{z_4^b}{\sum_{i=1}^m z_i^b}
\end{array} \right).
\end{align*}
\]

4.3. Multiagent Multi-Objective Optimization Model

4.3.1. Satisfaction Gap of Each FC Based on PZB

Parasuraman et al. proposed a service quality gap model for customer-perceived service quality promotion [9], widely named the Parasuraman–Zeithaml–Berry (PZB) service quality model. Gap 5 in the PZB model is the difference between the expected service and the perception of the service, which is most widely used in processing service quality promotion [28]. Similarly, Gap 5 in the PZB can also be applied in production innovation design after a little adjustment. In this paper, Gap 5 is redefined for the proposed scenario.

Definition 6. In this paper, Gap 5 is the difference between the performance expectation and the performance perception, calculated as follows:

\[
q_i^{e^p} = q_i^e - q_i^p,
\]
where \( q_{it}^e \) denotes the expectation of the functional performance of partial design scheme \( D_{it} \), which is estimated by the whole design group, and \( q_{it}^p \) denotes the perception of the functional performance of partial design scheme \( D_{it} \), which is estimated by the whole design group.

Practically, each FC can be designed using several partial design (P-design) schemes. In this case, the satisfaction degree of FC using different P-designs is crucial to select the ideal P-design to form the most suitable overall product innovation design scheme. This degree is determined by \( z_i = \{ \tilde{z}_i^1, \tilde{z}_i^2 \} \) (the relative weights of the FCs for multiagent requirements) and \( u \) (the synthesis functional performance of each FC for the enterprise through each P-design). \( z_i = \{ \tilde{z}_i^1, \tilde{z}_i^2 \} \) is obtained using Equations (2)–(14), while \( u \) is determined using complex factors. For easy calculation and understanding, the factors can be divided into two aspects: the enterprise providing ability of each P-design and the functional performance of each P-design.

On one hand, the enterprise providing ability is determined by many limited resources, such as the number of employees, the environment of the factory site, the performance of the manufacturing facilities, and the management ability of the enterprise. Accordingly, the providing ability of different P-designs for the same FC is different naturally, because it depends on different resources.

On the other hand, the functional components made using different P-designs also contribute different functional performance for achieving the same function.

These two aspects together determine \( u_{it} \), which can be calculated using Equation (16).

\[
\begin{align*}
  u_{it} &= p_{it} \otimes q_{it}^e. \\
  u_{it}^p &= p_{it} \otimes q_{it}^p. \\
  u_{it}^c &= p_{it} \otimes q_{it}^c.
\end{align*}
\]

Specially, the functional performance of each P-design is evaluated in terms of performance expectation \( q_{it}^e \) and performance perception \( q_{it}^p \). Accordingly, \( u_{it} \) is calculated in terms of expected value \( u_{it}^e \) and perceived value \( u_{it}^p \).

\[
\begin{align*}
  u_{it}^e &= p_{it} \otimes q_{it}^e. \\
  u_{it}^p &= p_{it} \otimes q_{it}^p.
\end{align*}
\]

Obviously, when \( p_{it} = 0 \), the enterprise is unable to manufacture \( D_i \) through \( D_{it} \), and, when \( p_{it} = 1 \), \( D_{it} \) can be completely used by the enterprise to manufacture \( D_i \). Normally, \( p_{it} \) is limited by the certainly of the enterprise; hence, it can be easily evaluated using a precise number. However, \( q_{it} \) is hard to describe comprehensively using a precise number. It should be evaluated using HFLTS to maintain linguistic information.

To calculate the ultimate satisfaction degree interval, \( q_{it}^e \) and \( q_{it}^p \) should be normalized. Correspondingly, \( u_{it}^c \) and \( u_{it}^p \) can satisfy the same criterion.

\[
\begin{align*}
  q_{it}^e &= \left( \begin{array}{c}
  \frac{q_{it}^{e,1}}{\sum_{t' = 1}^{m_i} q_{it'}^{e,1} + \sum_{t' = 1}^{m_i} q_{it'}^{e,2} + \sum_{t' = 1}^{m_i} q_{it'}^{e,3} + \sum_{t' = 1}^{m_i} q_{it'}^{e,4}} \\
  \frac{q_{it}^{e,2}}{\sum_{t' = 1}^{m_i} q_{it'}^{e,1} + \sum_{t' = 1}^{m_i} q_{it'}^{e,2} + \sum_{t' = 1}^{m_i} q_{it'}^{e,3} + \sum_{t' = 1}^{m_i} q_{it'}^{e,4}} \\
  \frac{q_{it}^{e,3}}{\sum_{t' = 1}^{m_i} q_{it'}^{e,1} + \sum_{t' = 1}^{m_i} q_{it'}^{e,2} + \sum_{t' = 1}^{m_i} q_{it'}^{e,3} + \sum_{t' = 1}^{m_i} q_{it'}^{e,4}} \\
  \frac{q_{it}^{e,4}}{\sum_{t' = 1}^{m_i} q_{it'}^{e,1} + \sum_{t' = 1}^{m_i} q_{it'}^{e,2} + \sum_{t' = 1}^{m_i} q_{it'}^{e,3} + \sum_{t' = 1}^{m_i} q_{it'}^{e,4}}
\end{array} \right), \\
  q_{it}^{e,1} &\leq 1
\end{align*}
\]

\[
\begin{align*}
  q_{it}^p &= \left( \begin{array}{c}
  \frac{q_{it}^{p,1}}{\sum_{t' = 1}^{m_i} q_{it'}^{p,1} + \sum_{t' = 1}^{m_i} q_{it'}^{p,2} + \sum_{t' = 1}^{m_i} q_{it'}^{p,3} + \sum_{t' = 1}^{m_i} q_{it'}^{p,4}} \\
  \frac{q_{it}^{p,2}}{\sum_{t' = 1}^{m_i} q_{it'}^{p,1} + \sum_{t' = 1}^{m_i} q_{it'}^{p,2} + \sum_{t' = 1}^{m_i} q_{it'}^{p,3} + \sum_{t' = 1}^{m_i} q_{it'}^{p,4}} \\
  \frac{q_{it}^{p,3}}{\sum_{t' = 1}^{m_i} q_{it'}^{p,1} + \sum_{t' = 1}^{m_i} q_{it'}^{p,2} + \sum_{t' = 1}^{m_i} q_{it'}^{p,3} + \sum_{t' = 1}^{m_i} q_{it'}^{p,4}} \\
  \frac{q_{it}^{p,4}}{\sum_{t' = 1}^{m_i} q_{it'}^{p,1} + \sum_{t' = 1}^{m_i} q_{it'}^{p,2} + \sum_{t' = 1}^{m_i} q_{it'}^{p,3} + \sum_{t' = 1}^{m_i} q_{it'}^{p,4}}
\end{array} \right), \\
  q_{it}^{p,1} &\leq 1
\end{align*}
\]

\[
\begin{align*}
  u_{it}^c &= p_{it} \otimes q_{it}^e = p_{it} \otimes \left( q_{it}^{e,1}, q_{it}^{e,2}, q_{it}^{e,3}, q_{it}^{e,4} \right). 
\end{align*}
\]
\[\hat{\alpha}_{ii}' = p_{ii}' \otimes \hat{\alpha}_{ii}' p_{ii}' \otimes (\hat{\alpha}_{ii}' p_{1}, \hat{\alpha}_{ii}' p_{2}, \hat{\alpha}_{ii}' p_{3}, \hat{\alpha}_{ii}' p_{4}). \quad (22)\]

\[\hat{\alpha}_{ii}^{-p} = \hat{\alpha}_{ii}' - \hat{\alpha}_{ii}' p_{ii}'. \quad (23)\]

Furthermore, the synthesis functional performances \(\hat{\alpha}_{ii}' p_{ii}'\) and \(\hat{\alpha}_{ii}^{-p}\) should be considered in conjunction with the relative weights of the FCs for multiagent requirements to obtain the satisfaction degree of \(D_i\) by \(D_{ii}'\) with respect to the multiagent group,

\[Q^e(u_{ii}') = z_i \otimes \hat{\alpha}_{ii}'. \quad (24)\]

\[Q^p(u_{ii}') = z_i \otimes \hat{\alpha}_{ii}' p_{ii}'. \quad (25)\]

Due to the relative weight of the FCs for multiagent requirements \(z_i\) divided into \(z_i^a\) and \(z_i^b\), \(Q(u_{ii}')\) needs to be separately calculated.

\[Q^{e,a}(u_{ii}') = z_i^a \otimes \hat{\alpha}_{ii}'. \quad (26)\]

\[Q^{p,a}(u_{ii}') = z_i^a \otimes \hat{\alpha}_{ii}' p_{ii}'. \quad (27)\]

\[Q^{e,b}(u_{ii}') = z_i^b \otimes \hat{\alpha}_{ii}'. \quad (28)\]

\[Q^{p,b}(u_{ii}') = z_i^b \otimes \hat{\alpha}_{ii}' p_{ii}'. \quad (29)\]

Then, the satisfaction degree interval can be generated.

\[Q^{-p,a}(u_{ii}') = Q^{e,a}(u_{ii}') - Q^{p,a}(u_{ii}') = (Q_{e-p,a}'^1, Q_{e-p,a}'^2, Q_{e-p,a}'^3, Q_{e-p,a}'^4). \quad (30)\]

\[Q^{-p,b}(u_{ii}') = Q^{e,b}(u_{ii}') - Q^{p,b}(u_{ii}') = (Q_{e-p,b}'^1, Q_{e-p,b}'^2, Q_{e-p,b}'^3, Q_{e-p,b}'^4). \quad (31)\]

In fact, the value of this interval may be negative. Thus, a positive transformation is necessary for building the subsequent optimization model.

\[\overline{Q}^{-e-p,a}(u_{ii}') = (Q_{e-p,a}'^1, Q_{e-p,a}'^2, Q_{e-p,a}'^3, Q_{e-p,a}'^4), \quad (32)\]

\[\overline{Q}^{-e-p,b}(u_{ii}') = (Q_{e-p,b}'^1, Q_{e-p,b}'^2, Q_{e-p,b}'^3, Q_{e-p,b}'^4). \quad (33)\]

Next, the centroid points of trapezoidal fuzzy numbers \(\overline{Q}^{-e-p,a}(u_{ii}')\), \(\overline{Q}^{-e-p,b}(u_{ii}')\), \(\overline{Q}^{e-p,a}(u_{ii}')\), and \(\overline{Q}^{e-p,b}(u_{ii}')\) can be calculated as follows:

\[\overline{Q}^{e-p,a}(u_{ii}') = \frac{3}{2} \times \frac{3 \times (\overline{Q}_{e-p,a})^2 + (\overline{Q}_{e-p,b})^2 - (Q_{e-p,a})^2 - 3 \times (Q_{e-p,b})^2}{Q_{e-p,a} + Q_{e-p,b} - Q_{e-p,a} - Q_{e-p,b}}. \quad (34)\]

\[\overline{Q}^{e-p,b}(u_{ii}') = \frac{3}{2} \times \frac{3 \times (\overline{Q}_{e-p,a})^2 + (\overline{Q}_{e-p,b})^2 - (Q_{e-p,a})^2 - 3 \times (Q_{e-p,b})^2}{Q_{e-p,a} + Q_{e-p,b} - Q_{e-p,a} - Q_{e-p,b}}. \quad (35)\]
These numbers can then be normalized for easier observation.

\[ \hat{Q}^{p,\alpha}(u_{ij'}) = \frac{\tilde{Q}^{p,\alpha}(u_{ij'})}{\sum_{i'=1}^{m'} \tilde{Q}^{p,\alpha}(u_{ij'})}, \] (36)

\[ \hat{Q}^{p,\beta}(u_{ij'}) = \frac{\tilde{Q}^{p,\beta}(u_{ij'})}{\sum_{i'=1}^{m'} \tilde{Q}^{p,\beta}(u_{ij'})}. \] (37)

4.3.2. Multiagent Multi-Objective Optimization Model

After determining the ultimate key indicators for product innovation design, the multiagent multi-objective optimization model can be established with total budget constraints.

For the proposed method, the budget of each functional component includes the cost of all stages from design to installation, denoted by \( c_{ii'} \). Furthermore, the aggregation of \( c_{ii'} \) is limited by the total budget of product innovation design, \( TC \), given by the enterprise.

In addition, \( x_{ii'} \) should be employed to describe the adoption of partial design scheme \( D_{ii'} \). It should be noted that variable \( x_{ii'} \) is either 1 or 0, because only one P-design is chosen each corresponding FC, i.e., \( x_{ii'} = (0, 1) \). When \( x_{ii'} = 1 \), P-design \( D_{ii'} \) is chosen; when \( x_{ii'} = 0 \), P-design \( D_{ii'} \) is eliminated. Finally, optimization model I can be established.

Model I:

\[ F(x) = [F_{\min}^{p,\alpha}(x), F_{\min}^{p,\beta}(x)], \] (38)

\[ F_{\min}^{p,\alpha}(x) = \sum_{i=1}^{m} \sum_{i'=1}^{m'} \tilde{Q}^{p,\alpha}(u_{ij'}) \times x_{ij'}, \] (39)

\[ F_{\min}^{p,\beta}(x) = \sum_{i=1}^{m} \sum_{i'=1}^{m'} \tilde{Q}^{p,\beta}(u_{ij'}) \times x_{ij'}, \] (40)

\[ \sum_{i'=1}^{m'} x_{ij'} = 1, \] (41)

\[ \sum_{i=1}^{m} \sum_{i'=1}^{m'} x_{ij'} \times c_{ii'} \leq TC, \] (42)

where \( F_{\min}^{p,\alpha}(x) \) represents the minimum satisfaction degree interval of the overall product design scheme to customers. \( F_{\min}^{p,\beta}(x) \) represents the minimum satisfaction degree interval of the overall product design scheme to design engineers.

However, solving this model is time-consuming, which contradicts the original intention of this method (to quickly and accurately generate the most suitable innovation design schemes). The NSGA-II algorithm with an elitist strategy was proposed by Deb [44,45], which can be applied to quickly and accurately solve model I with two key indicators, non-dominance rank and congestion distance. The concepts and main operations of the NSGA-II algorithm can be found in [44,45]. Typically, the NSGA-II algorithm may generate an optimal solution set including several solutions, i.e., the Pareto solution set represented by the Pareto optimal surface.

4.3.3. Multiagent Optimization Model Based on Model I

In model I, the importance of market demand and enterprise demand is not determined. If the importance of these two aspects can be determined, model I can be converted into a single-objective multiagent optimization model, named model II. In this case, \( \rho_1 \) and \( \rho_2 \) should be introduced to represent the importance of customer requirements and design engineering requirements, respectively.
Model II:

$$\max \Phi = \rho_1 \sum_{i=1}^{m} \sum_{i'=1}^{m'} Q_{i'j}^{\ell} - p_{i'j} (u_{i'j}) \times x_{i'j} + \rho_2 \sum_{i=1}^{m} \sum_{i'=1}^{m'} Q_{i'j}^{\ell} - p_{i'j} (u_{i'j}) \times x_{i'j}, \quad (43)$$

$$\sum_{i'=1}^{m'} x_{i'j} = 1,$$

$$\sum_{i=1}^{m} \sum_{i'=1}^{m'} x_{i'j} \times c_{i'j} \leq TC,$$

$$0 \leq \rho_1, \rho_2 \leq 1, \quad \rho_1 + \rho_2 = 1.$$

5. Case Study

In recent decades, global environmental pollution has become increasingly serious. It can be widely agreed that promoting new-energy usage, such as solar power, wind power, and hydraulic power, can significantly reduce environmental damage. However, these energy sources are difficult to store, which limits the promotion of new-energy applications. The XX company is dedicated to promoting new-energy applications. Their main products are photovoltaic modules and energy storage batteries for households. The household batteries are designed to store energy through the photovoltaic power generation panel (PV panel) in conditions of sufficient daylight or through the grid when electricity consumption is low, subsequently providing electricity in scenarios of power outage, unstable power supply, or electricity consumption peak time. The whole solar panel with storage battery product is shown in Figure 6. For society, this product can reduce the power consumption produced using fossil fuels, thereby reducing carbon emissions. On the other hand, for households, this product can be combined with PV panels to not only decrease electricity costs, but also provide an effective solution to ensure power supply to areas at the end of the grid or even off-grid. With the goal of quickly promoting the use of household batteries to more families, the XX company continuously invests in the innovation design of household storage batteries. Their aim is to meet market demand as best as possible and maximize the optimization requirements of enterprise design engineers. Hence, this scenario was chosen as a case study to validate the practicality and feasibility of the proposed method.

The innovation design group for the XX company’s product consists of 15 industry experts. The market subgroup has seven experts, and the enterprise subgroup has eight experts. Innovation focuses on the basic battery element and the management system of the whole storage battery system, ignoring the solar elements and the original home elements.

Firstly, questionnaires were distributed to 50 key customers and 20 product design engineers to collect their requirements. Then, 47 valid customer questionnaires and 20 valid product design engineer questionnaires were retained after filtering. Secondly, these requirements from customers and design engineers were evaluated to form the key multiagent requirement list through four rounds of the Delphi method. Specifically, the aim of the first round as to eliminate irrelevant requirements through expert evaluation, while the aim of the second round was to form the original main requirement list. Subsequently, the third and fourth rounds focused on generating the final requirement list. The list is shown in Table 3.

| Multiagent Requirements |
|--------------------------|
| **Customer requirements** | Long service life | Safety | Low-energy waste | Large battery capacity | Smart operation and monitoring |
| **Design engineering requirements** | Safety | Easy installation | Smart management system | Environmentally friendly | Stable and reliable |
The innovation design group for the XX company's product consists of 15 industry experts. The market subgroup has seven experts, and the enterprise subgroup has eight experts. Innovation focuses on the basic battery element and the management system of the whole storage battery system, ignoring the solar elements and the original home elements.

Firstly, questionnaires were distributed to 50 key customers and 20 product design engineers to collect their requirements. Then, 47 valid customer questionnaires and 20 valid product design engineer questionnaires were retained after filtering. Secondly, these requirements from customers and design engineers were evaluated to form the key multiagent requirement list through four rounds of the Delphi method. Specifically, the aim of the first round as to eliminate irrelevant requirements through expert evaluation, while the aim of the second round was to form the original main requirement list. Subsequently, the third and fourth rounds focused on generating the final requirement list. The list is shown in Table 3.

Table 3. The multiagent requirement list after four rounds of the Delphi method.

| Multiagent Requirements       | Customer requirements | Design engineering requirements |
|------------------------------|-----------------------|---------------------------------|
|                              | Long service life     | Safety                          |
|                              |                       | Low-energy waste                |
|                              |                       | Large battery capacity          |
|                              | Smart operation and   |                                 |
|                              | monitoring            |                                 |
|                              |                       |                                 |
|                              | Safety                | Easy installation               |
|                              |                       | Smart management system         |
|                              |                       |                                 |
|                              | Environmentally       | Stable and reliable             |
|                              | friendly               |                                 |

The household storage battery can be split into several functional components to determine the fundamental functions of the product. The structure of the whole battery is shown in Figure 7, where the management system of the battery consists of one element in the battery and a gateway outside.

Figure 6. The household storage battery system.

Figure 7. The structure of innovation design elements of household storage battery.
Next, a questionnaire targeting the relevance of functional components with respect to the customer requirements was distributed to the market group, while a questionnaire targeting the relevance of functional components with respect to the design engineering requirements and the self-correlation of functional components was distributed to the enterprise group. Then, the aggregates of these linguistic evaluations were translated into trapezoidal fuzzy numbers according to Table 2. After the transformation, these fuzzy numbers were calculated using Equations (2)–(10) to fill the HoQ.

In this stage, the first step was to collect the evaluations, as shown in Tables 4–6.

**Table 4.** The relationship between CRs and FCs in HFLTS (one expert in market subgroup).

| Requirements                  | Battery | Storage Invertor | Thermal and Noise Control | Management System | Shell of Product |
|-------------------------------|---------|------------------|---------------------------|-------------------|-----------------|
| Long service life             | (SR, TR)| NR               | WR                        | (NR, SSR)         | (NR, SSR)       |
| Safety                        | (SSR, SR, TR)| (NR, SSR, SR, TR)| (SSR, SR, TR)          | SSR              | (SSR, SE, TR)   |
| Low-energy waste              | (SR, TR)| NR               | (WR, SWR)                 | (NR, SSR)         | (TU, WR, SWR)   |
| Large battery capacity        | (SR, TR)| TU               | TU                        | TU                | (TU, WR, SWR)   |
| Smart operation and monitoring| (TU, WR, SWR, NR)| NR             | (SWR, NR)                 | (SR, TR)          | TU              |

**Table 5.** The relationship between DRs and FCs in HFLTS (one expert in enterprise subgroup).

| Requirements                  | Battery | Storage Invertor | Thermal and Noise Control | Management System | Shell of Product |
|-------------------------------|---------|------------------|---------------------------|-------------------|-----------------|
| Safety                        | SR      | SR               | (TU, WR, SWR)            | (NR, SSR, SR)     | NR              |
| Easy installation             | NR      | (TU, WR, SWR)    | (TU, WR, SWR)            | TU                | (SSR, SR, TR)   |
| Smart management system       | NR      | SSR              | WR                        | (SR, TR)          | TU              |
| Environment friendly          | SR      | SWR              | (SWR, NR)                 | (NR, SSR)         | NR              |
| Stable and reliable           | SR      | NR               | NR                        | SR                | WR              |

**Table 6.** The evaluations of self-correlation of FCs in HFLTS (whole innovation design group).

| Self-Relationship | Battery | Storage Invertor | Thermal and Noise Control | Management System | Shell of Product |
|-------------------|---------|------------------|---------------------------|-------------------|-----------------|
| Battery           | TR      | Storage Invertor | SR                        | TR                | WR              |
| Thermal and control | SSR  | TR               | SR                        | TR                | WR              |
| Management system | NR      | SSR              | NR                        | TR                | TR              |
| Shell of product  | WR      | WR               | NR                        | TU                | TR              |

After collecting the evaluations, the HFLTSs were aggregated into an agent group HFLTS, which was then transformed into the envelope of HFLTS according to Definitions 4 and 5 and Example 2. Furthermore, env(HFLTS) was presented as trapezoidal fuzzy numbers according to Table 1, and then normalized according to Equations (5)–(7). Specifically, the market aspect evaluation was chosen as an example to explain the calculation process, as shown in Tables 7–10.

**Table 7.** The aggregated relationship between CRs and FCs in HFLTS (whole market subgroup).

| Requirements                  | Battery | Storage Invertor | Thermal and Noise Control | Management System | Shell of Product |
|-------------------------------|---------|------------------|---------------------------|-------------------|-----------------|
| Long service life             | (SR, TR)| (NR, SSR)        | (WR, SWR, NR, SSR)        | (NR, SSR)         | (NR, SSR)       |
| Safety                        | (SSR, SR, TR)| (NR, SSR, SR, TR)| (NR, SSR, SR, TR)          | (NR, SSR)         | (NR, SSR)       |
| Low-energy waste              | (SR, TR)| (NR, SSR)        | (WR, SWR, NR, SSR)        | (NR, SSR)         | (NR, SSR)       |
| Large battery capacity        | (SR, TR)| TU               | TU                        | TU                | (TU, WR, SWR)   |
| Smart operation and monitoring| (TU, WR, SWR, NR)| (TU, WR, SWR, NR)| (SWR, NR)                | (SSR, SR, TR)     | TU              |
Table 8. The envelope of HFLTS (whole market subgroup).

| Requirements                        | Battery     | Storage Inverter | Thermal and Noise Control | Management System | Shell of Product |
|-------------------------------------|-------------|------------------|---------------------------|-------------------|------------------|
| Long service life                   | [SR, TR]    | [NR, SSR]        | [WR, SSR]                 | [NR, SSR]         | [NR, TR]         |
| Safety                              | [SSR, TR]   | [NR, TR]         | [NR, TR]                  | [NR, SSR]         | [SSR, TR]        |
| Low-energy waste                    | [SSR, TR]   | [NR, SSR]        | [WR, SSR]                 | [SWR, SSR]        | [TU, SWR]        |
| Large battery capacity              | [SR, TR]    | TU               | TU                        | TU                | TU               |
| Smart operation and monitoring      | [TU, NR]    | [TU, NR]         | [SWR, NR]                 | [SSR, TR]         | TU               |

Table 9. Trapezoidal fuzzy numbers for envelope of HFLTS (whole market subgroup).

| Requirements                        | Battery     | Storage Inverter | Thermal and Noise Control | Management System | Shell of Product |
|-------------------------------------|-------------|------------------|---------------------------|-------------------|------------------|
| Long service life                   | (0.692, 0.769, 1, 1) | (0.385, 0.462, 0.692, 0.769) | (0.077, 0.154, 0.692, 0.769) | (0.385, 0.462, 0.692, 0.769) | (0.385, 0.462, 1, 1) |
| Safety                              | (0.538, 0.615, 1, 1) | (0.385, 0.462, 1, 1) | (0.385, 0.462, 1, 1) | (0.385, 0.462, 0.692, 0.769) | (0.538, 0.615, 1, 1) |
| Low-energy waste                    | (0.538, 0.615, 1, 1) | (0.385, 0.462, 0.692, 0.769) | (0.077, 0.154, 0.692, 0.769) | (0.231, 0.308, 0.692, 0.769) | (0.0, 0, 0.385, 0.462) |
| Large battery capacity              | (0.692, 0.769, 1, 1) | (0.0, 0, 0.077, 0.154) | (0.0, 0, 0.077, 0.154) | (0.0, 0, 0.077, 0.154) | (0.0, 0, 0.385, 0.462) |
| Smart operation and monitoring      | (0.0, 0.538, 0.615) | (0.0, 0.538, 0.615) | (0.231, 0.308, 0.538, 0.615) | (0.538, 0.615, 1, 1) | (0.0, 0.077, 0.154) |

Table 10. The normalized trapezoidal fuzzy numbers of envelope of HFLTS (whole market subgroup).

| Requirements                        | Battery     | Storage Inverter | Thermal and Noise Control | Management System | Shell of Product |
|-------------------------------------|-------------|------------------|---------------------------|-------------------|------------------|
| Long service life                   | (1, 1, 1, 1) | (1, 1, 0.692, 0.769) | (0.2, 0.333, 0.692, 0.769) | (0.716, 0.751, 0.692, 0.769) | (0.716, 0.751, 1, 1) |
| Safety                              | (0.777, 0.8, 1, 1) | (1, 1, 1, 1) | (1, 1, 1, 1) | (0.716, 0.751, 0.692, 0.769) | (1, 1, 1, 1) |
| Low-energy waste                    | (0.777, 0.8, 1, 1) | (1, 1, 0.692, 0.769) | (0.2, 0.333, 0.692, 0.769) | (0.429, 0.501, 0.692, 0.769) | (0.0, 0.385, 0.462) |
| Large battery capacity              | (1, 1, 1, 1) | (0, 0, 0.077, 0.154) | (0, 0, 0.077, 0.154) | (0, 0, 0.077, 0.154) | (0.0, 0.385, 0.462) |
| Smart operation and monitoring      | (0, 0, 0.538, 0.615) | (0, 0, 0.538, 0.615) | (0.6, 0.667, 0.538, 0.615) | (1, 1, 1, 1) | (0.0, 0.077, 0.154) |

The normalized trapezoidal fuzzy numbers of each evaluation were filled into the HoQ, as shown in Table 9. Then, the relative weights of FCs for each multiagent requirement were calculated for the HoQ. Firstly, the weight vector of the customer requirements was \( W = (0.15, 0.35, 0.10, 0.21, 0.20) \), as determined by the market subgroup, and the weight vector of the design engineering requirements was \( V = (0.29, 0.17, 0.19, 0.12, 0.23) \), as determined by the enterprise subgroup. Secondly, \( z_{\alpha}^i \) and \( z_{\beta}^i \) were calculated using Equations (8)–(14). Then, these relative weights were filled into the HoQ framework, as shown in Table 11.

Combining the new technique and the current household storage battery solutions on the market, the XX company proposed several partial design (P-design) schemes of each FC, as shown in Table 12. For example, the D41 P-design can be achieved through the digital improvement of the XX company, while the D11 P-design is inspired by the high-capacity characteristics of other household storage batteries on the market. Furthermore, the satisfaction degree interval of each P-design with respect to the multiagent requirements was calculated using Equations (15)–(40). The key indicators for this calculation process are shown in Table 13.

According to the key indicators derived from the above calculations, model I was established as follows:

\[
F(x) = \left[ f^{x-P}_{\alpha}^{-P}(x), f^{x-P}_{\beta}^{-P}(x) \right],
\]

\[
f^{x-P}_{\alpha}^{-P}(x) = 0.3478 \times x_{11} + 0.2983 \times x_{12} + 0.3538 \times x_{13} + \cdots + 0.3301 \times x_{54},
\]

\[
f^{x-P}_{\beta}^{-P}(x) = 0.3271 \times x_{11} + 0.3078 \times x_{12} + 0.3651 \times x_{13} + \cdots + 0.3287 \times x_{54},
\]

\[
x_{11} + x_{12} + x_{13} = 1,
\]
\[ x_{21} + x_{22} = 1, \]
\[ x_{31} + x_{32} = 1, \]
\[ x_{41} + x_{42} + x_{43} = 1, \]
\[ x_{51} + x_{52} + x_{53} + x_{54} = 1, \]
\[ \sum_{i=1}^{m} \sum_{j'=1}^{m'} x_{ij} \times c_{ij} \leq TC. \]

**Table 11.** The HoQ for innovation design.

| Self-correlation | Battery | Storage Invertor | Thermal and Noise Control | Management System | Shell of Product |
|------------------|---------|------------------|----------------------------|-------------------|-----------------|
|                   | (1, 1, 1) | (0.091, 0.167, 0.692, 0.769) | (0.455, 0.501, 1, 0.167) | (0.091, 0.167, 0.538, 0.615) | (0, 0, 0.231, 0.308) |
|                   | (0.091, 0.167, 0.692, 0.769) | (1, 1, 1) | (0.273, 0.334, 0.692, 0.769) | (0.273, 0.334, 0.692, 0.769) | (0, 0, 0.231, 0.308) |
|                   | (0.455, 0.501, 1, 1) | (0.273, 0.334, 0.692, 0.769) | (1, 1, 1) | (0.091, 0.167, 0.538, 0.615) | (0.455, 0.501, 0.538, 0.615) |
|                   | (0.091, 0.167, 0.538, 0.615) | (0.273, 0.334, 0.692, 0.769) | (0.091, 0.167, 0.538, 0.615) | (1, 1, 1) | (0, 0, 0.077, 0.154) |
|                   | (0, 0, 0.231, 0.308) | (0, 0, 0.231, 0.308) | (0.455, 0.501, 0.538, 0.615) | (0, 0, 0.077, 0.154) | (1, 1, 1) |

**Table 12.** The P-design list for each functional component.

| Functional Components | P-Designs | Detailed Description of P-Designs | Cost (USD) |
|-----------------------|-----------|-----------------------------------|------------|
| D1—Battery            | D11       | Ternary lithium battery, usage energy 16.2 kWh, maximum continuous power 8.1 kW, peak power 10 kW | 2300       |
|                       | D12       | Ternary lithium battery, usage energy 13.5 kWh, maximum continuous power 5.8 kW, peak power 7.2 kW | 1800       |
|                       | D13       | Lithium iron phosphate batteries, usage energy 13.5 kWh, maximum continuous power 5.8 kW, peak power 7.2 kW | 1400       |
| D2—Invertor           | D21       | Less than 10% charge/discharge loss | 400        |
|                       | D22       | Less than 8% charge/discharge loss | 350        |
In this scenario, the total budget was 3350 USD, i.e., TC = 3350. NSGA-II with an elitist strategy was applied to quickly generate the solutions of the model. The result is shown in Table 14, and the innovation design scheme selection based on model II is shown in Table 15.

Table 13. The normalized values of satisfaction degree intervals.

| P-Design | $p_{it}$ | $Q_{it}^{e}$ | $Q_{it}^{u}$ | $Q_{it}^{e}$ | $Q_{it}^{u}$ | $Q^{-P_{it}}(u_{it})$ | $Q^{-P_{it}}(u_{it})$ |
|----------|----------|--------------|--------------|--------------|--------------|----------------|----------------|
| D11      | 0.7305   | (0.0807, 0.0969, 0.1774, 0.1936) | (0.1128, 0.129, 0.234, 0.2533) | (0.059, 0.0708, 0.1256, 0.1414) | (0.0699, 0.0838, 0.106, 0.1179) | 0.2385 | 0.2834 |
| D12      | 0.8653   | (0.1451, 0.1613) | (0.1128, 0.129) | (0.0484, 0.0646, 0.1451, 0.1613) | (0.0457, 0.0609, 0.1672, 0.1824) | 0.2532 | 0.2765 |
| D13      | 0.9423   | (0.1914, 0.2127, 0.234, 0.2533) | (0.1914, 0.2127, 0.234, 0.2533) | (0.1173, 0.1341, 0.1909, 0.2177) | (0.1509, 0.1677, 0.1845, 0.2013) | 0.3478 | 0.3271 |
| D21      | 0.8653   | (0.1451, 0.1613) | (0.1128, 0.129) | (0.0484, 0.0646, 0.1451, 0.1613) | (0.0457, 0.0609, 0.1672, 0.1824) | 0.2385 | 0.2834 |
| D22      | 0.7883   | (0.1164, 0.1397, 0.2093, 0.2325) | (0.234, 0.2533) | (0.218, 0.234) | (0.1845, 0.2013) | 0.1128 | 0.129 |
| D31      | 0.7305   | (0.0807, 0.0969, 0.1774, 0.1936) | (0.1128, 0.129, 0.234, 0.2533) | (0.059, 0.0708, 0.1256, 0.1414) | (0.0699, 0.0838, 0.106, 0.1179) | 0.2385 | 0.2834 |
| D32      | 0.8653   | (0.1451, 0.1613) | (0.1128, 0.129) | (0.0484, 0.0646, 0.1451, 0.1613) | (0.0457, 0.0609, 0.1672, 0.1824) | 0.2385 | 0.2834 |
| D41      | 0.8653   | (0.1451, 0.1613) | (0.1128, 0.129) | (0.0484, 0.0646, 0.1451, 0.1613) | (0.0457, 0.0609, 0.1672, 0.1824) | 0.2385 | 0.2834 |
| D42      | 0.8653   | (0.1451, 0.1613) | (0.1128, 0.129) | (0.0484, 0.0646, 0.1451, 0.1613) | (0.0457, 0.0609, 0.1672, 0.1824) | 0.2385 | 0.2834 |
| D43      | 0.9423   | (0.1451, 0.1613) | (0.1128, 0.129) | (0.0484, 0.0646, 0.1451, 0.1613) | (0.0457, 0.0609, 0.1672, 0.1824) | 0.2385 | 0.2834 |
| D51      | 0.9423   | (0.1451, 0.1613) | (0.1128, 0.129) | (0.0484, 0.0646, 0.1451, 0.1613) | (0.0457, 0.0609, 0.1672, 0.1824) | 0.2385 | 0.2834 |
| D52      | 0.9423   | (0.1451, 0.1613) | (0.1128, 0.129) | (0.0484, 0.0646, 0.1451, 0.1613) | (0.0457, 0.0609, 0.1672, 0.1824) | 0.2385 | 0.2834 |
| D53      | 0.9423   | (0.1451, 0.1613) | (0.1128, 0.129) | (0.0484, 0.0646, 0.1451, 0.1613) | (0.0457, 0.0609, 0.1672, 0.1824) | 0.2385 | 0.2834 |
| D54      | 0.9423   | (0.1451, 0.1613) | (0.1128, 0.129) | (0.0484, 0.0646, 0.1451, 0.1613) | (0.0457, 0.0609, 0.1672, 0.1824) | 0.2385 | 0.2834 |

Table 14. The result of NSGA-II.

| Overall Innovation Design | Satisfaction Degree Interval of Customer | Satisfaction Degree Interval of Designer | Cost (USD) |
|---------------------------|-----------------------------------------|----------------------------------------|------------|
| OID1: D12, D21, D32, D42, D51 | 1.7707 | 1.8041 | 3170 |
| OID2: D12, D22, D31, D41, D51 | 1.8049 | 1.7851 | 3310 |
| OID3: D12, D22, D32, D42, D52 | 1.7779 | 1.7869 | 3130 |
Table 15. The selection of final innovation design.

| Number | \( \rho_1 \) | \( \rho_2 \) | \( OID_1 - \max \Phi \) | \( OID_2 - \max \Phi \) | \( OID_3 - \max \Phi \) |
|--------|-------------|-------------|----------------|----------------|----------------|
| 1      | 0.4         | 0.6         | 1.79074        | 1.79302        | 1.7833         |
| 2      | 0.5         | 0.5         | 1.7874         | 1.7950         | 1.7824         |
| 3      | 0.6         | 0.4         | 1.78406        | 1.79698        | 1.7815         |

In model II, after determining the weights of the customer group and designer group, i.e., \( \rho_1 \) and \( \rho_2 \), the final innovation design was selected from the above results. The selection of this scenario is shown in Table 15.

If the innovation design group prefers customer demand to designer demand, i.e., \( \rho_1 = 0.4 \) and \( \rho_2 = 0.6 \), the overall innovation design 3 would be chosen due to the lowest \( \max \Phi \).

6. Conclusions

This paper studied the incremental innovation design of new-energy storage according to multiagent group decision making in a fuzzy environment. The proposed method for selecting the most suitable innovation design scheme considered the preference of the multiagent group with uncertainties. Specifically, the two main aspects (CR and DR) were considered to present the requirements of the market and enterprise. The uncertainties of their vague preferences and evaluations were quantified using the HFLTS with envelope and trapezoidal fuzzy numbers.

For the total process of innovation in this paper, the first step was to collect and select the requirements for the multiagent group. Then, the HoQ of QFD was extended into a two-dimension framework for adaptation to the multiagent GDM. Furthermore, the evaluation of the relationship of FCs with multiagent requirements and the self-correlation of FCs was presented using the HFLTS with envelope, enabling more comprehensive linguistic information to be maintained with low loss due to uncertainties. Next, the satisfaction degree interval was calculated according to the theory of the PZB model. In addition, for calculation of the proposed method, the uncertainties of evaluation at each step were qualified using trapezoidal fuzzy numbers after HFLTS and context-free grammar. Lastly, a model was proposed to analyze new-energy storage battery innovation to select a better overall design scheme to improve competitiveness. The model fully considered the different crucial groups and the fuzzy environment of multiple agents for product innovation in a real-life scenario.

The main contributions of this paper can be divided into two aspects. On the one hand, we considered the effectiveness of market demands and technical improvements through CR and DR. The adjusted QFD is more suitable for multiagent product innovation to convert the requirements into technical characteristics. On the other hand, evaluation using HFLTS with envelope enables decision makers to collect more comprehensive linguistic information with vagueness. The product performance gap and the satisfaction degree interval can better reflect the view of multiple agents. Moreover, the proposed method is clear to understand and easy to operate, thus providing a foundation for further research on environmentally friendly product innovation.

Improving the competitiveness of a product is the core of innovation in enterprises. Grasping the vital requirements, improving the suitable techniques, promoting the product’s aesthetics, adjusting the functional structure, etc. are meaningful endeavors to improve competitiveness. This paper focused on innovation design for a new-energy storage battery in the trend of environmental protection. The proposed method demonstrates high feasibility and flexibility, and it can be widely used for innovation in manufacturing enterprises. The processing of the fuzzy environment and the evaluation of vague information can be used in GDM applications. Innovation is a complex question, which is not always addressed by customers and designers. In further research, the requirements of suppliers can be considered. In addition, more attention can be paid to obtaining the optimal model using more suitable intelligent algorithms.
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