mathematics

Article

Extension Design Pattern of Requirement Analysis for Complex Mechanical Products Scheme Design

Tichun Wang *, Hao Li and Xianwei Wang

College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China
* Correspondence: wangtichun2010@nuaa.edu.cn

Abstract: Due to the configuration process of a complex product scheme, a design structure often has the characteristics of multi-level, multi-attribute, creativity, and complexity; in order to improve the efficiency and quality of product scheme design, it has important research value to reasonably organize, reason, and reuse design knowledge. In this paper, the extension modeling problem under the extension design mode of complex product scheme is studied, the multitype design knowledge element modeling expression model of complex product scheme design is given, and the extension process model and the implication process model of requirement analysis of complex product scheme design is established. A new demand element weight assignment method based on extension distance is proposed to obtain accurate demand analysis index weight from the perspective of combined qualitative and quantitative analysis. On the basis of constructing the extension correlation degree of demand primitives, this paper puts forward the implementation method of the extension design pattern for the demand analysis of a complex product scheme design and gives the specific implementation algorithm. Finally, an example of product design is given to illustrate the method, and the results show the effectiveness and operability of the method.

Keywords: intelligent design; data analysis; models and algorithms; extension theory; scheme design

MSC: 68T20

Citation: Wang, T.; Li, H.; Wang, X. Extension Design Pattern of Requirement Analysis for Complex Mechanical Products Scheme Design. *Mathematics* **2022**, *10*, 3132. https://doi.org/10.3390/math10173132

Academic Editor: Bo-Hao Chen

Received: 5 July 2022
Accepted: 12 August 2022
Published: 1 September 2022

1. Introduction

The product scheme design of the aerospace industry or power generation equipment industry is creative, skilled labor based on the combination of some theories and a large amount of practical experience; its design process is a multi-level multi-attribute creative and complex configuration process, the interaction of various design factors generate design constraints and design conflicts in the design process [1–4], so accurately describing analyzing and transforming the customers' requirements is very important for the smooth development of the product. Requirement analysis is not only considering the customer's requirement information but also considering the information of the entire life cycle of the product, that is, the design's feasibility, manufacturability, reliability, maintainability, energy, and environmental protection; they are the design goals of the various activities in the product development process to make requirements analysis better guide the subsequent design. Because of that, scheme design cannot, in isolation, describe the requirement model from the customer's point of view; it should consider the entire life cycle of the product and strive to make the requirement model, and not only output necessary design requirements but also be conducive to the mapping between product's function and structure, and lay the foundation for product design automation [5–7].

Currently, many scholars analyze and discuss the customer's requirements from different perspectives and give its corresponding method of requirement analysis [8–11], but it usually has some problems, such as the formalization of requirement description is not enough or the information of product requirements lack objectivity [12–14]. Extenics, which is founded by Chinese scholar Professor Cai Wen, is an emerging discipline; it uses a formal model to study the possibility of object extension, and its pioneering and innovative rules and methods use formal implementation to search the rules of contradiction issues from qualitative and quantitative angles [15–17]. Extenics, which depends on basic element theory and extension mathematics, formalize the process of solving problems to establish the corresponding mathematical model and, on the basis of it, develops a new calculation method and technology that is more intelligent and formally resolves the issue of deep knowledge's storage representation and processing in the knowledge base [18,19], to promote knowledge in knowledge engineering more formal, deeper, and more fundamental. At present, extenics has some successful applications in the field of product design [15,20–23], but the study of systematically applying extenics in requirement analysis of complex mechanical products is rare, and it is still in its infancy. Axiomatic design is a new conceptual product design theory proposed by Suh of MIT in the early 1990s. Its purpose is to establish a scientific basis for complex product design and improve design activities in product development by providing designers with thinking methods and tools based on logic and rationality [24–27]. Different from the research method of discrete products [28,29], the research method of this paper is the extension intelligent design method, which aims to study and analyze the extension and implication of design problems in the process of requirement analysis of complex product scheme design. The formal modeling problem of design knowledge is solved by establishing a knowledge model, the extension reasoning problem of requirement analysis is solved by establishing a requirement analysis process model, and the extension design mode of requirement analysis is established to realize the extension requirement analysis of complex product scheme design.

Therefore, on the basis of integrating extension design and axiomatic design, and the relevant design methods and the concept of optimal solution [30–33]. This paper studies the extension process model and implication process model of requirement analysis in complex product concept design. Due to the problem of multi-attribute and multi-parameter requirement analysis, we put forward an allocation model of requirement basic element weight based on extensible distance, calculated the extensible relational degree of requirement basic element from the angle of a combination of qualitative and quantitative, and constructed the framework of extension design pattern of requirement analysis for complex mechanical product scheme design. In this paper, we will give the specific process with examples. Firstly, the extension modeling for the extension design pattern of concept design is given in Section 2. Then, the extension design pattern of requirement analysis of conceptual design is described in Section 3. Then, an extension design pattern of requirement analysis for complex mechanical products scheme design is provided in Section 4. Finally, the discussions and acknowledgments are given in Sections 5 and 6, respectively.

2. Extension Modeling for Extension Design Pattern of Concept Design

Due to dealing with the various complex design reasoning problems in product concept design, it needs to solve the issue of deep knowledge's storage representation and processing in the process of concept design reasoning. For this, extenics introduces basic element theory into product concept design; it takes a basic element as the logic cell of extensible design, and it gathers the represented design object's quality, quantity, action, and relation into an ordered triple $\boldsymbol{J} = (\Gamma, c, v)$ which is constituted of the design object Γ, object's characteristics c and the value v of characteristics. Formal modeling describes the information action and relation in the design process and puts forward a new methodology system for people to know the world and solve contradictions in the real world.

2.1. The Basic Element Modeling of Multitype Design Knowledge

On the basis of the semantic segmentation method multitype, design information in the conceptual design process is analyzed and arranged to form the minimum complete independent units of design information that can represent the design characteristics. Due to the manifestations of different units, we can establish the corresponding design knowledge units; formal and modeling describe it by basic element. In this paper, the design information in the conceptual design is divided into static design information, behavioral design information, and relational design information.

When modeling the static design information, we can describe it by the matter element model $\boldsymbol{J}(\boldsymbol{R})$, which belongs to basic element theory. If the design object has characteristics, then its matter element model $\boldsymbol{J}(\boldsymbol{R})$ is as below:

$$\boldsymbol{J}(\boldsymbol{R}) = \begin{bmatrix} \Gamma(N) & C(N)_1 & [V(C)_1, W(C)_1] \\ & C(N)_2 & [V(C)_2, W(C)_2] \\ & \vdots & \vdots \\ & C(N)_n & [V(C)_n, W(C)_n] \end{bmatrix} \tag{1}$$

Among it, $\Gamma(N)$ describes the name of the object, $V(C)$ is the value of design characteristic, $W(C)$ is the weight of design characteristic, $V(C)$ and $W(C)$ have many forms such as the value of precise point, interval value with Fuzzy Information, subordinate function, the qualitative semantic description, and so on. Thus, in order to express more general, assuming $V = \left[v^L, v^R\right]$, $W = \left[w^L, w^R\right]$, both of them are interval values with Fuzzy Information, then Formula (1) can be expressed as follows:

$$\boldsymbol{J}(\boldsymbol{R}) = \begin{bmatrix} \Gamma(N) & C(N)_1 & \left(\left[v(C)_1^L, v(C)_1^R\right], \left[w(C)_1^L, w(C)_1^R\right]\right) \\ & C(N)_2 & \left(\left[v(C)_2^L, v(C)_2^R\right], \left[w(C)_2^L, w(C)_2^R\right]\right) \\ & \vdots & \vdots \\ & C(N)_n & \left(\left[v(C)_n^L, v(C)_n^R\right], \left[w(C)_n^L, w(C)_n^R\right]\right) \end{bmatrix} \tag{2}$$

When modeling the behavioral design information, we can describe it by the affair element model $\boldsymbol{J}(\boldsymbol{I})$, which belongs to basic element theory. If the design object has m characteristics, then its affair element model $\boldsymbol{J}(\boldsymbol{I})$ is as below:

$$\boldsymbol{J}(\boldsymbol{I}) = \begin{bmatrix} \Gamma(D) & B(D)_1 & \left(U(B)_1, \left[w(B)_1^L, w(B)_1^R\right]\right) \\ & B(D)_2 & \left(U(B)_2, \left[w(B)_2^L, w(B)_2^R\right]\right) \\ & \vdots & \vdots \\ & B(D)_m & \left(U(B)_m, \left[w(B)_m^L, w(B)_m^R\right]\right) \end{bmatrix} \tag{3}$$

Among it, $\Gamma(D)$ is the name of design behavior, $B(D)$ is the operating characteristic of design behavior, and $W(B)$ is the weight of operating characteristic.

When modeling the relational design information, we can take the relational element model $\boldsymbol{J}(\boldsymbol{Q})$ to describe the configuration relationship, logical relationship, implication relationship, comparative relationship, and assembly relationship in the design process; if the design constraints relationship has characteristics, then its relational element model $\boldsymbol{J}(\boldsymbol{Q})$ is as below:

$$\boldsymbol{J}(\boldsymbol{Q}) = \begin{bmatrix} \Gamma(S) & A(S)_1 & \left(G(A)_1, \left[w(A)_1^L, w(A)_1^R\right]\right) \\ & A(S)_2 & \left(G(A)_2, \left[w(A)_2^L, w(A)_2^R\right]\right) \\ & \vdots & \vdots \\ & A(S)_k & \left(G(A)_k, \left[w(A)_k^L, w(A)_k^R\right]\right) \end{bmatrix} \tag{4}$$

Among it, $\Gamma(S)$ is the name of the design constraints relationship, $A(S)$ is the relational characteristic of the design constraints relationship, and $W(A)$ is the weight of the relational characteristic.

In the process of complex product conceptual design, the design knowledge often has mixing characteristics; that is, the combination of static design information, behavioral design information, and relational design information; for this, we describe it by the compound element model $\boldsymbol{J}(\boldsymbol{F})$, which belongs to basic element theory. Through the function of conjunction Θ to represent the multilayer semantic and more abundant design information, which is the frequently used conjunction, Θ is conjunction "$\wedge$" and/or conjunction "$\vee$" and forms the corresponding and compound element or compound element and/or compound element, thus forming the overall design information of scheme design. The compound element model $\boldsymbol{J}(\boldsymbol{F})$ can be expressed as follow:

$$\boldsymbol{J}(\boldsymbol{F}) = \begin{bmatrix} \Gamma(F) & (\Theta)\Gamma(\boldsymbol{J}(\boldsymbol{R}_i)) & (V(\boldsymbol{J}(\boldsymbol{R}_i)), W(\boldsymbol{J}(\boldsymbol{R}_i))) \\ & (\Theta)\Gamma(\boldsymbol{J}(\boldsymbol{I}_j)) & (V(\boldsymbol{J}(\boldsymbol{I}_j)), W(\boldsymbol{J}(\boldsymbol{I}_j))) \\ & (\Theta)\Gamma(\boldsymbol{J}(\boldsymbol{Q}_s)) & (V(\boldsymbol{J}(\boldsymbol{Q}_s)), W(\boldsymbol{J}(\boldsymbol{Q}_s))) \end{bmatrix} \tag{5}$$

Among it, i, j, s separately represent the number of matter element, affair element, and relational element.

It should be emphasized that when taking the above models as representing design knowledge, it only expresses a state of the design attributes and does not express the degree of importance; the weight will not have to be contained in the above models.

2.2. Construction of Extension Set of Basic Element

In the process of product design, the customer's requirements can be divided into two components of common requirements and personalized requirements. Common requirements are the customer's knowledge and requirements for the product convergence; for this part of the design, we generally use the existing classical structure model or variant structure of the existing structure model to accomplish the conceptual product design. Personalized requirements are the customer's special knowledge and requirements for the product, and conceptual product design is often required by attaining innovation or extension on the structure or function of the existing product. Thus, in order to meet the customer's requirements comprehensively, the design process has the characteristics of dynamics, diversity, relevance, and level; the existing dominant design information may not be able to fully meet the design requirements; for this, it needs to mine design knowledge and form a set of design knowledge to improve the innovation ability of conceptual design.

According to the basic element theory of extenics, we know that the basic element has properties of implication and extension; through extension transformation, we can obtain more abundant tacit knowledge and obtain the corresponding extension set; this provides a means of support for the smooth implementation of the conceptual product design.

(1) Implication and the set of the basic element. For basic element $\boldsymbol{J}_1$ and $\boldsymbol{J}_2$, if $\boldsymbol{J}_1$ exists, then $\boldsymbol{J}_2$ must exist, we call it $\boldsymbol{J}_1$ contains $\boldsymbol{J}_2$, recording it as $@\boldsymbol{J}_1 \Rightarrow @\boldsymbol{J}_2$, among it, @represents identification of existing. Because basic elements can be complex by conjunction Θ, the implication of basic element can be represented by $@\boldsymbol{J}_i\Theta@\boldsymbol{J}_j \Rightarrow @\boldsymbol{J}_s\Theta@\boldsymbol{J}_t$, among it, i, j, s, t all represent the number of basic elements. Form the implication set of basic elements by basic elements, which is obtained by implication. The implication of basic elements can transmit and transform, so we can carry out the reasoning of the conceptual design process by the implication.

(2) Extensibility and basic element extension set. The extensibility of basic elements contains three aspects: divergence, expansion, and relevance. In the design field, through carrying out extension transformation of basic element characteristics and the value of characteristics, on the one hand, it can create the ways and approaches for design objects to outward divergence and expand, and acquire the extension design knowledge in the design field, on the other hand, it can build relationships between design objects, and acquire the relational design knowledge in the design field. We can acquire an extension set of the basic element $\boldsymbol{S}(\boldsymbol{J})_T$ by extension transformation.

$$\begin{aligned} \boldsymbol{S}(\boldsymbol{J})_T = \Big\{ (\boldsymbol{J}, \Phi, \Psi) \Big| & \boldsymbol{J} \in T_{\Omega(\boldsymbol{J})}\Omega(\boldsymbol{J}),\ \Phi = K(\boldsymbol{J}) = k(X), \\ & \Psi = T_K K(T_{\boldsymbol{J}}\boldsymbol{J}) = T_k k(X^*),\ X = c(\boldsymbol{J}), X^* = c^*(T_{\boldsymbol{J}}\boldsymbol{J}) \Big\} \end{aligned} \tag{6}$$

Among it, T_Ω, T_K, and T_J separately represent design object $\boldsymbol{J}$'s extension transformation of the domain, correlation function, basic element characteristics, and its value. c is the evaluation characteristic of $\boldsymbol{J}$; its value is $X = c(\boldsymbol{J})$; c^* is the evaluation characteristic of $\boldsymbol{J}$ that is acquired by extension transformation T_J, its value is $X^* = c^*(T_J\boldsymbol{J})$; $\Phi = k(X)$ is the correlation function of evaluation characteristic, $\Psi = T_k k(X^*)$ is correlation function of evaluation characteristic that is acquired by extension transformation T_J.

By Equation (6), the objects in the existing basic element set can be subject to extension transformation in many ways, such as domain, correlation function, basic element feature, and eigenvalue, so as to obtain more extensive design knowledge in the design field and related design knowledge among the design fields, thus providing support for subsequent extension reasoning.

3. The Extension Design Pattern of Requirement Analysis of Conceptual

For the conceptual design of complex products, the customer's requirements generally have the characteristics of abstraction, ambiguity, variability, diversity levels, and relevance; this often troubles designers in obtaining a correct understanding of the customer's design purpose, and it affects the design quality and design efficiency of products. Thus, on the basis of extension theory, analyze the customer's requirements, transform the design requirement into an objective expression of formal and modeling product requirement information, clearly reflect the level relationship and relational characteristics of customer's requirements, make the requirements information transform into technology requirements information effectively to guide products conceptual design, on the basis of these, to make the requirement analysis of products conceptual design more reasonable comprehensive and standard.

3.1. The Extension Process Model of Requirement Analysis

Due to the requirement analysis of products can acquire the initial design scheme of products conceptual design, the model of requirement analysis will directly affect the subsequent product's whole process of design, manufacturing, use, and maintenance; it can be seen that requirement analysis is an important part in the process of product design. Thus, for requirement analysis of complex product conceptual design, we cannot, in isolation, describe the requirement model from the customer's requirements and should carry out requirement transformation from the angle of the product life cycle; this process involves the whole product life cycle information, such as the design feasibility, manufacturability, assembly, maintainability, reliability. Strive to make the requirement model useful for the relevance and mapping of customer domain, functional domains, structural domain, and process domain in conceptual product design, and then provides a theoretical foundation and practical means and methods for the automation of complex product design.

On the basis of basic element theory, we can build a basic element model for every requirements information in requirements analysis, separately build the matter-type requirement basic element model $\boldsymbol{J}(\boldsymbol{R})_C$, behavior-type requirement basic element model $\boldsymbol{J}(\boldsymbol{I})_C$, relation-type requirement basic element model $\boldsymbol{J}(\boldsymbol{Q})_C$ and compound -type requirement basic element model $\boldsymbol{J}(\boldsymbol{F})_C$. Matter-type requirement basic element model $\boldsymbol{J}(\boldsymbol{R})_C$ describes characteristics requirements, functional requirements, structural requirements, environmental requirements, performance requirements, and other aspects of static properties and design information. Behavior-type requirement basic element model $\boldsymbol{J}(\boldsymbol{I})_C$ describes design behavior-type information related to requirement analysis in the product design process, such as solving problems, judgment knowledge, process planning, and reasoning. Relation-type requirement basic element model $\boldsymbol{J}(\boldsymbol{Q})_C$ describes the various constraints or dependent information between requirement characteristics in the product design process, such as configuration relationship, comparative relationship, and logical relationship. The compound-type requirement basic element model $\boldsymbol{J}(\boldsymbol{F})_C$ is the combination of the various requirement basic elements. On the basis of the above basic element models, we can acquire the set of requirement basic element $\boldsymbol{S}(\boldsymbol{J})_{CT}$ and the corresponding knowledge database of various requirement basic elements. Based on the extension theory, the demand information is analyzed, evaluated, and transformed to form the subsequent product design information, which can better support the rapid design of complex products. The extension process model of requirement analysis in complex product conceptual design is shown in Figure 1.

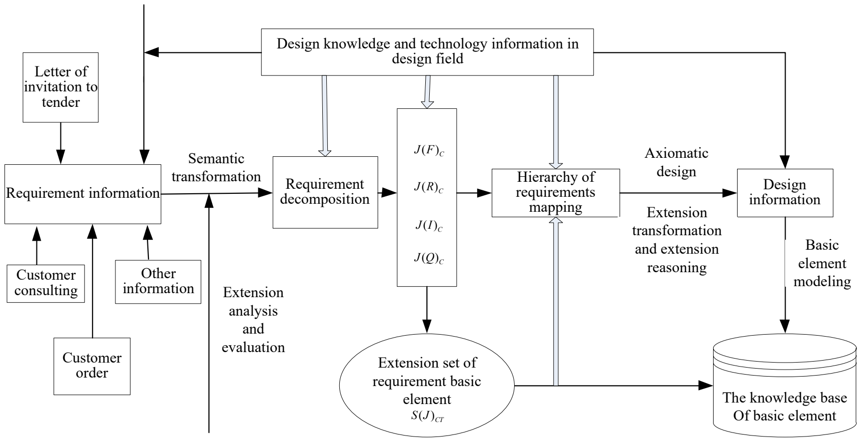

Figure 1. The extension process model of requirement analysis of complex product conceptual design.

It can be seen that after obtaining the corresponding demand information based on the relevant design requirements, the demand information can be decomposed based on semantic transformation and combined with extension analysis and evaluation methods, and then the primitive modeling can be carried out to form the extension set of demand primitives Extension reasoning and extension transformation are used to map the requirements hierarchically, so as to obtain the design information that meets the design requirements. After the primitive modeling, it is stored in the primitive knowledge base.

3.2. The Implication Process Model of Requirement Analysis

In the extension process model of the requirement of complex product conceptual design, after semantic transforming requirement information, extension analyzing, and evaluating it, we can acquire the minimum, complete, independent design information unit in the representation design process, and after modeling it, we can acquire its corresponding requirement basic element. By requirement analysis process of product design, we know that customer requirements in the field of product design can generally be divided into common customer requirements and individual customer requirements; common customer requirements are the converging understanding and requirements of the customers for the product in the design field, individual customer requirements are some special understanding and requirements based on common customer requirements.

Because the representation of common customer requirements is common design information in the design field, obviously, in order to provide improved support for the rapid design of the product, it needs effectively reuse this part of the common design information, which is a common requirement basic element. Because the basic elements have the property of implication, the experts in the design field use the method of analysis and evaluation or the method of data mining to acquire the implication relationship in the extension set of requirement analysis, and due to the implication relationship, in new product design, it only needs to match the condition items of implication, then we can reuse the result items of implication relationship, thus to effectively reuse existing design results, short the design cycle and improve the design efficiency. The implication process model of requirement analysis that is oriented toward the rapid design of the product is expressed as follows:

$$\begin{cases} \forall(J_{Cm}, J_{Cn})J_{Cm} \in \Omega \wedge J_{Cn} \in \Omega \wedge (J_{Cm}\Theta J_{Cn}) \in \Omega \wedge ((J_{Cm}\Theta J_{Cn}) \Rightarrow (J_s\Theta J_t)) \in \Omega, \quad m \neq n \\ if \quad @J_{C0i} \in \Omega \wedge @J_{C0j} \in \Omega \wedge @\left(J_{C0i}\Theta J_{C0j}\right) \in \Omega, \quad i \neq j \\ \exists\left(\left(J_{C0i}\Theta J_{C0j}\right)\Xi(J_{Cm}\Theta J_{Cn})\right) \wedge K\left(\left(J_{C0i}\Theta J_{C0j}\right)\Xi(J_{Cm}\Theta J_{Cn})\right) \geq K_0(\Omega) \\ then \quad \left(J_{C0i}\Theta J_{C0j}\right) \in S(J_{Cm}\Theta J_{Cn})_{CT} \end{cases} \tag{7}$$

Among it, J_{Cm} and J_{Cn} represent the existing requirement basic elements, J_s and J_t represent the basic elements of design result in extension set, J_{C0i} and J_{C0j} represent basic requirement elements in the process of requirement analysis, Ω represents discourse domain of design, Ξ represents matching identification of basic element model, $K((J_{C0i}\Theta J_{C0j})\Xi(J_{Cm}\Theta J_{Cn}))$ represents the matching degree of basic element model, $K_0(\Omega)$ represents the allowable matching threshold in discourse domain.

From the above implication process model of requirement analysis, it can be seen that when the match degree between the requirement basic element or its compound element and the existing requirement basic element or its compound element meets the given match threshold, the design results contained in the existing requirement basic element or its compound element can apply into product scheme design as an effective reusable object. In the extension multiplexing method of fast configuration conceptual design, the basic element matching algorithm based on extension theory is described.

3.3. The Weight Distribution Model of Requirement Basic Element Based on Extension Distance

The extension process model of requirement analysis based on complex product conceptual design can achieve the decomposition and mapping of the design requirements, but because requirement information in requirement analysis of conceptual product design has characteristics of fuzziness and relevance, the weight of requirement characteristics and design parameters is usually not easy to be determined. For this, this paper puts forwards a new method of weight allocation based on extension distance compared with the existing weight allocation method; the weight allocation method based on extension distance is an analysis method combined qualitative and quantitative, and it can preferably solve the problems that evaluation indicators are difficult to quantify and statistical in requirement analysis, and can exclude the impact of human factors, make the result of weight allocation more scientific, more objective and more accurate.

Assuming after decomposing the requirement, it has P requirement basic elements; According to the design requirement, it needs to invite Z experts in the design field; On the basis of importance degree of costumer's requirement, separate ratio scale of requirement basic element into 0~9, form the ratio scale interval $u_{ij} = [u_{ij}^l, u_{ij}^r]$; that is, j the expert evaluates the requirement basic element J_i, among it $0 \leq u_{ij}^l \leq 9$, $0 \leq u_{ij}^r \leq 9$, $u_{ij}^l \leq u_{ij}^r$. Thus acquire the ratio scale interval sequence of requirement basic element J_i that is expressed by $U(J_i) = ([u_{i1}^l, u_{i1}^r], [u_{i2}^l, u_{i2}^r], \cdots, [u_{iZ}^l, u_{iZ}^r])$. Build ideal ratio scale interval sequence of basic requirement element $U(J_0) = ([u_{01}^l, u_{01}^r], [u_{02}^l, u_{02}^r], \cdots, [u_{0Z}^l, u_{0Z}^r])$ based on P requirement basic elements' ratio scale interval sequence, and meets $[u_{0j}^l, u_{0j}^r] = \left[\max\limits_{1 \leq i \leq p} u_{ij}^l, \max\limits_{1 \leq i \leq p} u_{ij}^r\right]$.

Then construct the extension relational coefficient ρ_{ij} that is $U(J_i)$ and $U(J_0)$ concerning j the scale value based on extension distance:

$$\begin{aligned} \rho_{ij} = \rho\left(\left[u_{ij}^l, u_{ij}^r\right], \left[u_{0j}^l, u_{0j}^r\right]\right) &= \frac{\rho\left(u_{ij}^l, \left[u_{0j}^l, u_{0j}^r\right]\right) + \rho\left(u_{ij}^r, \left[u_{0j}^l, u_{0j}^r\right]\right)}{2} \\ &= \frac{\left(\left|u_{ij}^l - \frac{u_{0j}^l + u_{0j}^r}{2}\right| - \frac{1}{2}\left(u_{0j}^r - u_{0j}^l\right)\right) + \left(\left|u_{ij}^r - \frac{u_{0j}^l + u_{0j}^r}{2}\right| - \frac{1}{2}\left(u_{0j}^r - u_{0j}^l\right)\right)}{2} \end{aligned} \tag{8}$$

Then the extension degree λ_i between $U(\boldsymbol{J}_i)$ and $U(\boldsymbol{J}_0)$ is:

$$\lambda_i = \frac{1}{Z}\sum_{j=1}^{Z}\left(9 - \rho_{ij}\right) \tag{9}$$

Then the relatively of requirement is expressed by:

$$w_{Ui} = \lambda_i / \sum_{i=1}^{P}\lambda_i \tag{10}$$

Thus, obtaining the sequence of the weight of basic requirement element $w_U = [w_{U1}, w_{U2}, \cdots, w_{UP}]^T$, and meet $\sum_{i=1}^{P} w_{Ui} = 1$.

The weight distribution of basic elements of design parameters obtained by mapping requirements analysis takes each basic element of demand as the standard, that is, the scale interval of each basic element of demand as the ideal scale interval, and the extension correlation coefficient is calculated. Assuming it has $\boldsymbol{Q}$ design parameters and basic elements, it needs to invite $\boldsymbol{Z}$ experts in the design field. On the basis of the importance degree of costumer's requirement, a separate ratio scale of requirement basic element into 0~9 acquire design parameter basic element $\boldsymbol{J}_k$'s ratio scale interval sequence $V(\boldsymbol{J}_k) = (lbracku^l_{k1}, u^r_{k1}], [u^l_{k2}, u^r_{k2}], \cdots, [u^l_{kZ}, u^r_{kZ}]), k = 1, 2, \cdots, P$. By using the above similarly processing process, take the requirement basic element $\boldsymbol{J}_i$ as the evaluation standard, then the extension relational degree λ_{ik} between design parameter basic element $\boldsymbol{J}_k$ and requirement basic element $\boldsymbol{J}_i$ can be expressed by:

$$\begin{aligned}\lambda_{ik} &= \tfrac{1}{Z}\sum_{j=1}^{Z}\rho\left(\left[v^l_{kj}, v^r_{kj}\right], \left[u^l_{ij}, u^r_{ij}\right]\right) = \tfrac{1}{Z}\sum_{j=1}^{Z}\left(9 - \frac{\rho\left(v^l_{kj}, \left[u^l_{ij}, u^r_{ij}\right]\right) + \rho\left(v^r_{kj}, \left[u^l_{ij}, u^r_{ij}\right]\right)}{2}\right) \\ &= \tfrac{1}{Z}\sum_{j=1}^{Z}\left(9\text{-}\frac{\left(\left|v^l_{kj} - \frac{u^l_{ij}+u^r_{ij}}{2}\right| - \frac{1}{2}\left(u^r_{ij} - u^l_{ij}\right)\right) + \left(\left|v^r_{kj} - \frac{u^l_{ij}+u^r_{ij}}{2}\right| - \frac{1}{2}\left(u^r_{ij} - u^l_{ij}\right)\right)}{2}\right)\end{aligned} \tag{11}$$

On the basis of it, we can acquire an extension relational degree matrix $\mathrm{A}_{\boldsymbol{J}}$ between Q design parameter basic elements and P requirement basic elements:

$$\mathrm{A}_{\boldsymbol{J}} = \begin{bmatrix} \lambda_{11} & \lambda_{12} & \cdots & \lambda_{1Q} \\ \lambda_{21} & \lambda_{22} & \cdots & \lambda_{2Q} \\ \vdots & \vdots & \vdots & \vdots \\ \lambda_{P1} & \lambda_{P2} & \cdots & \lambda_{PQ} \end{bmatrix}_{P\times Q} \tag{12}$$

The design parameter basic element weighting extension relational degree sequence w_V based on requirement basic element weight sequence is:

$$w_V = w_U^T * \mathrm{A}_{\boldsymbol{J}} = [w_1, w_2, \ldots, w_P]_{1\times P} * \begin{bmatrix} \lambda_{11} & \lambda_{12} & \cdots & \lambda_{1Q} \\ \lambda_{21} & \lambda_{22} & \cdots & \lambda_{2Q} \\ \vdots & \vdots & \vdots & \vdots \\ \lambda_{P1} & \lambda_{P2} & \cdots & \lambda_{PQ} \end{bmatrix}_{P\times Q} \tag{13}$$

Then absolutely weight w_{Vk} of design parameter basic element $\boldsymbol{J}_k$ is:

$$w_{Vk} = \textstyle\sum_{i=1}^{P}(w_{Ui} * \lambda_{ik}), 1 \le i \le P \tag{14}$$

Then absolutely weight w^*_{Vk} of design parameter basic element $\boldsymbol{J}_k$ is:

$$w^*_{Vk} = w_{Vk} / \textstyle\sum_{k=1}^{Q} w_{Vk} \tag{15}$$

From these, acquire design parameter basic element weight sequence $w_V = \left[w^*_{V1}, w^*_{V2}, \cdots, w^*_{VQ}\right]^T$, and meets $\sum_{k=1}^{Q} w_{Vk} = 1$.

3.4. The Implementation of Extension Design Pattern of Requirement Analysis

The final result of product conceptual design requirements analysis can effectively map the design parameters of subsequent products, including functional design parameters, structural design parameters, and process design parameters. The essence of extension design for requirement analysis of conceptual product design effectively transformed the basic requirement element into a design parameter basic element and formed an extensible design frame. Based on extension theory and axiomatic design, the traditional QFD is improved, and a demand analysis extension design mode that transforms customer requirements into design parameters is proposed. Compared with traditional quality function deployment QFD [34,35], the extension design pattern of requirement analysis is not just formulate the product planning or improve the product structure; it also uses the improved quality function deployment QFD to acquire design information that guides and runs through the product lifecycle. Figure 2 gives the frame of implementation of the extension design pattern of requirement analysis.

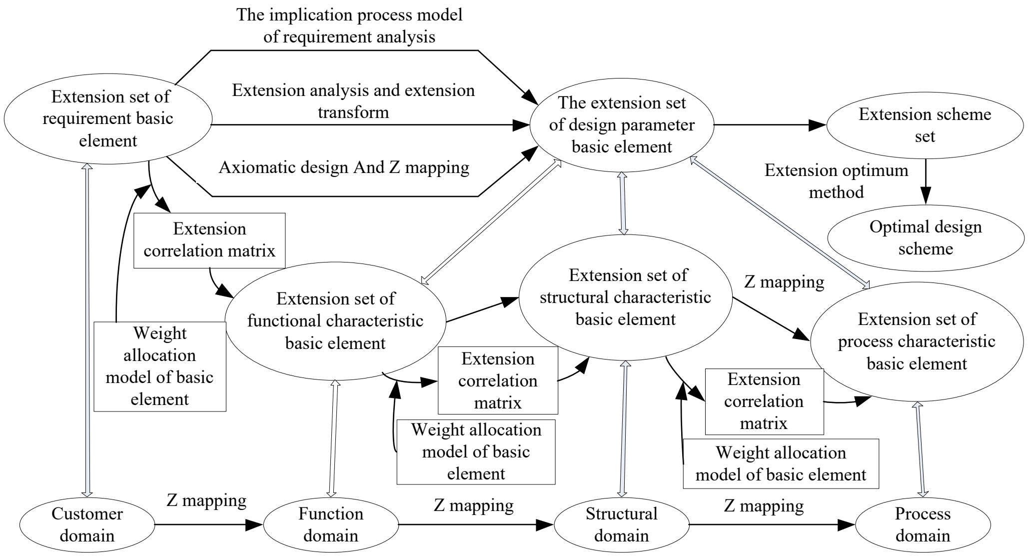

Figure 2. The extension design pattern of requirement analysis of conceptual product design.

It can be seen from Figure 2 that the extension design mode of product scheme design requirement analysis divides the process of product scheme design requirement analysis into customer domain, function domain, structure domain, process domain, etc. The extension set of the basic requirement element corresponds to the extension modeling of the customer domain. The extension set of the design parameter basic element includes the extension set of the functional characteristic basic element, the extension set of the structural characteristic basic element, and the extension set of the process characteristic basic element. The extension set of the functional characteristic basic element corresponds to the extension modeling of the functional domain, the extension set of the structural characteristic basic element corresponds to the extension modeling of the structural domain, and the extension set of process characteristic basic element corresponds to the extension modeling of the process domain. Based on axiomatic design theory, adjacent design domains have corresponding mapping relations, which can be realized by z-mapping. Similarly, the corresponding basic element extension sets of adjacent design domains also have corresponding z-mapping and corresponding extension incidence matrix. By using the demand analysis implication process model, extension analysis and extension transformation, and the z-mapping of axiomatic design, the extension set of the design parameter basic element and extension scheme set is generated, and the optimal design scheme is obtained based on the extension optimization method. The extension optimization method will be discussed in detail in the subsequent papers. It needs to be explained here that the effective construction of the extension set of the design parameter basic element is acquired by the combination of Z mapping in the design field, the implication process model of requirement analysis, and the method of extension analysis and transformation. Specifically, by Z mapping in the design field based on axiomatic design, design parameters commonly have the structural characteristics of the level association. However, using compound elements can formally and, with modeling, describe the design parameters which have the structural characteristics of the level association so that the product extension design can be implemented smoothly.

In summary, the implementation steps of the extension design pattern of requirement analysis for conceptual product design can be expressed as follow:

Step1: Acquire requirement information in the design field, decompose the requirement, build the unit of requirement information, and build the model of the basic requirement element.

Step 2: Construct the extension set of the basic requirement element, and build the implication process model of the basic requirement element.

Step 3: On the basis of axiomatic design, hierarchical Z-mapping requirement basic element in customer domain into design parameter basic element in function domain, structural domain, and process domain, transform the design parameters combined with the implication process model of requirement basic element and its relational extension transformation method and acquire its relational extension set of design parameter basic element.

Step 4: Construct a weight allocation model of the basic requirement element, and build an extension correlation matrix in different design fields.

Step 5: On the basis of the basic element knowledge base, rule base, and case base that is constructed in the design field, they match the design parameter basic element to acquire the set of conceptual design schemes.

4. Application Example

This paper takes a selection scheme of large-scale hydropower turbines as an example to describe the implementation of extension design patterns for complex products. Due to the different areas of local geology, topography, water quality, current, and the environment have a big difference, so the design requirement of hydroelectric power stations in the different regions has characteristics of diversity and dynamic; it needs a variety of types of turbines to meet the corresponding design requirements. However, because the large turbine design theory is imperfect, the internal fluid motion of the turbine is complex, and the production model of turbine design has characteristics of a single piece, small-batch, and large sets; these make the large turbine design process have characteristics that are multi-level, multi-attribute, multi-constrained and multi-objective, and the implementation of the design scheme becomes very cumbersome. Therefore, based on the extension design mode of complex products, this paper conducts an extension analysis of design requirements for a large turbine selection scheme, determines the design domain of turbine products, and obtains the basic design parameters of a large turbine selection scheme in the design domain.

It is known that a large-scale hydropower's geographical environment is a multi-mountainous region; its terrain is relatively steep, the water's silt content is high, the water flow is relatively large, and the head is relatively high. Table 1 gives the design requirement parameters of a hydropower station.

Table 1. The Design and Exploitation Requirement Parameters of a Hydropower Station.

Requirement Item	The Value of Requirement	Requirement Item	The Value of Requirement
Average annual flow	$\geq$235.0 m^3/s	Design flow	$\geq$307.0 m^3/s
Maximum head	126.0 m	Minimum head	86.0 m
Design head	112.0 m	Rated power	$\geq$300.0 MW
Maximum power	$\geq$306.0 MW	Rated speed	125.0 r/min
Runaway rotation rate	$\leq$260.0 r/min	Prototype efficiency	$\geq$93.5%
Amount of leakage	$\leq$0.1 m^3/s	Control mode	Automatic control
Operational stability	Long-term stability	Energy consumption property	Low
Environmental protection property	Less pollution	Noise property	Low
Structure type	Compact	Runner weight	Light

To make a selection design of the turbine, you must first determine the direction of the design of the turbine, that is, determine the structure type of turbine based on the actual situation of hydropower, such as geology, topography, water quality, and water flow. According to the experience in the field of design, we know that large turbine structure type contains Francis, axial, oblique flow, tubular, and pelton, and each type of turbine applies to different conditions; it is generally determined by the head, power, load changes, sediment concentration, flow, etc. By analyzing the hydropower station's requirement information, we know that the hydropower station has a high head, medium-power, medium load changes, high sediment concentration, and large water flow, so it is suitable to use a Francis turbine. By experts' analysis, discussion, and evaluation, the hydropower design requirement information is broken down into common requirement information and individual requirement information; the specific content is shown in Table 2.

Table 2. The Decomposition of Design Requirement Information.

Design Direction	The Category of Requirement Information	Requirement Characteristic	
Francis turbine	Common requirement	Head	
		Output	
	Information	Efficiency	
		Cavitation property	
		Runaway property	
	Individual requirement information	Operation controllability	Automatic control
			Simple, safe
		Environmental protection and energy saving property	Low energy consumption
			Low pollution
			Low noise
		Structure type and weight	Compact
			Light

For common requirement information, new product design parameters can be obtained based on common design requirements templates in the design field; For individual requirement information, due to the diversity of information change, there are no corresponding templates to be chosen, and we need to take an approach that is same as common design requirements templates to the analysis, that is transformation and mapping among the customer domain, functional domains, structure domain and process domain based on the axiomatic design theory to obtain the corresponding product design parameters.

Figure 3 shows the framework of the Francis turbine's common design requirements information template based on axiomatic design theory and extension theory.

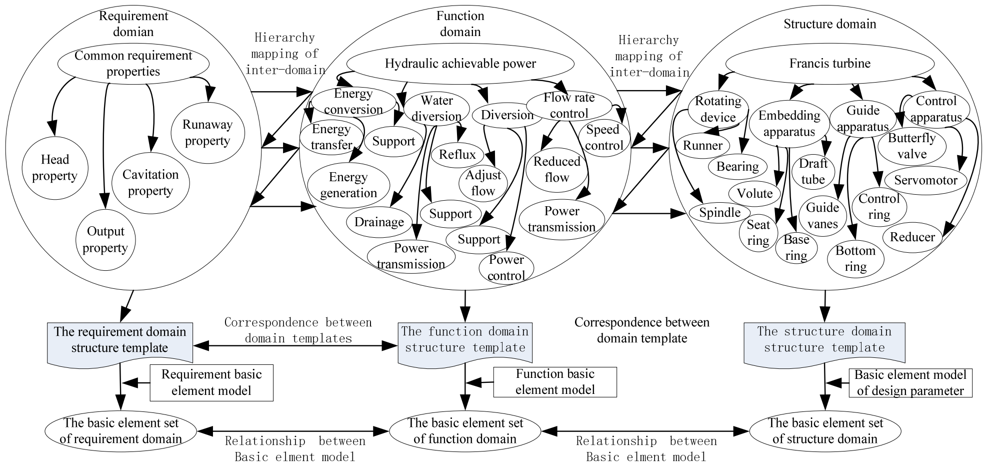

Figure 3. The framework of the Francis turbine's common design requirements information template.

It can be seen from Figure 3 that the common design requirement information template for the hydraulic turbine includes three parts: the requirement domain, the functional domain, and the structural domain. For different design domains, the corresponding design domain structural template and the corresponding basic element set can be generated; that is, the requirement domain corresponds to the requirement domain structural template and the requirement domain basic element set, and the functional domain corresponds to the functional domain structural template and the functional domain basic element set. The structure domain corresponds to the structure template of the structure domain and the basic element set of the structure domain. Based on the axiomatic design theory, it can be seen that the structure template of the demand domain, the structure template of the function domain, and the structure template of the structure domain have the same mapping relationship. Similarly, there is the same mapping relationship between the demand domain basic element set, the functional domain basic element set, and the structure domain basic element set.

Quick configuration of the selection of the turbine design is to determine the turbine's critical flow path model such as runner, volute, draft tube, the guide vane, and so on. In shunt turbine general design requirements information as you can see, in the framework of the template, volute, guide tube, and turbine guide vane wheel are key design components in turbine products secondary components devices, thus determine key flow turbine model can obtain the key design parameters of the turbine design, be able to support the smooth implementation of subsequent turbine design. To this end, in the framework of the common Francis turbine design requirements template, we use the extension process model of requirement analysis to model the design requirement information and two object-type basic elements to describe design requirement items in Table 1, which are fundamental design parameter requirement basic element $\boldsymbol{J}(\boldsymbol{R})_{C0\text{-}D}$ and auxiliary design parameter requirement basic element $\boldsymbol{J}(\boldsymbol{R})_{C0\text{-}P}$. The fundamental design parameter requirement basic element $\boldsymbol{J}(\boldsymbol{R})_{C0\text{-}D}$ is used to design the runner model and volute, draft tube, the guide vane flow path model, and the auxiliary design parameter requirement basic element $\boldsymbol{J}(\boldsymbol{R})_{C0\text{-}P}$ is used to assist and guide selection design of the turbine.

$$J(\boldsymbol{R})_{C0\text{-}D} = \begin{bmatrix} \text{Basic design requirements} & \text{Maximum head } H_{\max}\ (\text{m}) & 126.0 \\ & \text{Rated head } H_0\ (\text{m}) & 112.0 \\ & \text{Minimum head } H_{\min}\ (\text{m}) & 86.0 \\ & \text{Design flow } Q_d\ (\text{m}^3/\text{s}) & \geq 307.0 \\ & \text{Average flow } Q_v\ (\text{m}^3/\text{s}) & \geq 235.0 \\ & \text{Rated power } P_r\ (\text{MW}) & \geq 300.0 \\ & \text{Maximum power } P_{\max}\ (\text{MW}) & \geq 306.0 \\ & \text{Rated rotation rate } n_r\ (\text{r/min}) & 125.0 \\ & \text{Runaway rotation rate } n_R\ (\text{r/min}) & \leq 260.0 \\ & \text{Amount of leakage } q\ (\text{m}^3/\text{s}) & \leq 0.1 \\ & \text{Efficiency } \eta & \geq 93.3\% \end{bmatrix}$$

$$J(\boldsymbol{R})_{C0\text{-}P} = \begin{bmatrix} \text{Auxiliary design requirement} & \text{Control mode} & \text{Automation} \\ & \text{Operational stability} & \text{Long-term} \\ & \text{Energy consumptionproperty} & \text{Low} \\ & \text{Environmental protection property} & \text{Less pollution} \\ & \text{Noise property} & \text{Low} \\ & \text{Structure type} & \text{Compact} \\ & \text{Wheelweight} & \text{Light} \end{bmatrix}$$

After modeling the design information, it can build the corresponding extension set of basic elements and the basic element knowledge base. Therefore, according to the fundamental design parameter requirement, basic element $J(\boldsymbol{R})_{C0\text{-}D}$'s head to retrieve basic element knowledge base and acquire runner model which meets head range requirements, the matched runner, basic element models, in basic element knowledge base are as below:

$$J_{Turb\text{-}Runner01} = \begin{bmatrix} D257 & \text{Maximum head } H_{\max}\ (\text{m}) & 109.5 \\ & \text{Rated head } H_0\ (\text{m}) & 101.1 \\ & \text{Minimum head } H_{\min}\ (\text{m}) & 62.1 \\ & \text{Rated power } P_r\ (\text{MW}) & 102.0 \\ & \text{Maximum power } P_{\max}\ (\text{MW}) & 114.3 \\ & \text{Efficiency } \eta & 93.53 \end{bmatrix}$$

$$J_{Turb\text{-}Runner02} = \begin{bmatrix} A630 & \text{Maximum head } H_{\max}\ (\text{m}) & 143.0 \\ & \text{Rated head } H_0\ (\text{m}) & 119.9 \\ & \text{Minimum head } H_{\min}\ (\text{m}) & 83.0 \\ & \text{Rated power } P_r\ (\text{MW}) & 310.0 \\ & \text{Maximum power } P_{\max}\ (\text{MW}) & 340.0 \\ & \text{Efficiency } \eta & 93.20 \end{bmatrix}$$

$$J_{Turb\text{-}Runner03} = \begin{bmatrix} D203 & \text{Maximum head } H_{\max}\ (\text{m}) & 135.6 \\ & \text{Rated head } H_0\ (\text{m}) & 130.5 \\ & \text{Minimum head } H_{\min}\ (\text{m}) & 114.5 \\ & \text{Rated power } P_r\ (\text{MW}) & 408.2 \\ & \text{Maximum power } P_{\max}\ (\text{MW}) & 408.8 \\ & \text{Efficiency } \eta & 92.57 \end{bmatrix}$$

$$J_{Turb\text{-}Runner04} = \begin{bmatrix} A364 & \text{Maximum head } H_{\max}\ (\text{m}) & 121.5 \\ & \text{Rated head } H_0\ (\text{m}) & 106.7 \\ & \text{Minimum head } H_{\min}\ (\text{m}) & 80.7 \\ & \text{Rated power } P_r\ (\text{MW}) & 310.0 \\ & \text{Maximum power } P_{\max}\ (\text{MW}) & 330.0 \\ & \text{Efficiency } \eta & 94.00 \end{bmatrix}$$

According to the experience in the selection of the turbine design, we know that when it meets head range requirements, the power and efficiency are the main basis for selecting the runner model. It can be seen that in matched runner basic element models, $J_{Turb\text{-}Runner01}$ cannot meet the power design requirement, $J_{Turb\text{-}Runner03}$ cannot meet the efficiency design requirement. Although $J_{Turb\text{-}Runner02}$ and $J_{Turb\text{-}Runner04}$ both can meet the power design requirement and efficiency design requirement when rated power and maximum power are close, $\boldsymbol{J}_{Turb\text{-}Runner04}$ has higher efficiency, so $\boldsymbol{J}_{Turb\text{-}Runner04}$ is the best runner matching object in the basic element knowledge base.

Take basic element model $\boldsymbol{J}_{Turb\text{-}Runner04}$'s name as the condition item for the extension process model of requirement analysis, use the classic frequent pattern tree algorithm (FP_growth), set condition item $A364$ as the root node of frequent pattern tree, carry out frequent pattern mining among runner models and volute, draft tube, guide vane's flow path models in basic element knowledge base and rule base. If the acquired frequent pattern meets the requirements of the support and confidence, then we can acquire a strong implication relationship between runner model and volute, draft tube, guide vane's flow path models, that is $\boldsymbol{J}_{Turb\text{-}Runner04}|A364 \Rightarrow J_{WK\text{-}94}|A364$, $\boldsymbol{J}_{Turb\text{-}Runner04}|A364 \Rightarrow J_{DY\text{-}43}|A364$, $\boldsymbol{J}_{Turb\text{-}Runner04}|A364 \Rightarrow J_{WSG\text{-}51}|A364$. According to the extension implication relationship, and on the basis of volute $\boldsymbol{J}_{WK\text{-}94}|A364$, draft tube $A364 \Rightarrow \boldsymbol{J}_{WSG\text{-}51}$ and guide vane $\boldsymbol{J}_{DY\text{-}43}|A364$, we can carry out selection design of volute, draft tube, guide vane's flow path which is associated to target runner.

At the same time, although $\boldsymbol{J}_{Turb\text{-}Runner04}$ is the best runner matching object in the basic element knowledge base, $\boldsymbol{J}_{Turb\text{-}Runner04}$'s property parameters are not fully compliant with design requirements; for this, it needs to carry out an extension transform for the value of characteristics of $\boldsymbol{J}_{Turb\text{-}Runner04}$, that is use expertise of turbine to analyze and optimize the value of characteristics of $\boldsymbol{J}_{Turb\text{-}Runner04}$, acquire reasonable nominal diameter of runner, rotational rate and flow path combination which meet force requirement and have high efficiency, and then to determine the other design parameters of target runner. On the basis of the description in the paper, combined with knowledge in the turbine design field, and according to the comprehensive characteristic curve of the existing turbine runner, we can first take the maximum head, design head, and head range as the characteristics of extension transform, take the force and efficiency as constraints of extension transform, to carry out multi-level reasoning analysis for runner $\boldsymbol{J}_{Turb\text{-}Runner04}$, find design parameter combination of matched runner's unit speed and unit flow in the comprehensive characteristic curve of the turbine runner. If the design parameter combination meets the design requirements, then take it as an extension reuse object; If the design parameter combination cannot meet the design requirements, it needs to take unit speed and unit flow as characteristics of extension transform to carry out the next level extension transformation, and so forth, ultimately acquire runner basic element model that meets requirements:

$$J_{Turb\text{-}TA364\text{-}1} = \begin{bmatrix} \text{Runner } TA364\text{-}1 & \text{Nominal diameter } D_1 \text{ (m)} & 5.50 \\ & \text{Maximum height } H_1 \text{ (m)} & 2.92 \\ & \text{Design flow } Q_d \text{ (m}^3\text{/s)} & 307.00 \\ & \text{Rated rotation rate } n_r \text{ (r/min)} & 125.00 \\ & \text{Runaway rotation rate } n_R \text{ (r/min)} & \leq 260.0 \\ & \text{Efficiency } \eta \text{ (\%)} & 94.30 \\ & \text{Reliability } \Gamma \text{ (\%)} & 95.00 \end{bmatrix}$$

$$J_{Turb\text{-}TA364\text{-}2} = \begin{bmatrix} \text{Runner } TA364\text{-}2 & \text{Nominal diameter } D_1 \ (m) & 5.775 \\ & \text{Maximum height } H_1 \text{ (m)} & 3.202 \\ & \text{Design flow } Q_d \text{ (m}^3\text{/s)} & 301.20 \\ & \text{Rated rotation rate } n_r \text{ (r/min)} & 136.40 \\ & \text{Runaway rotation rate } n_R \text{ (r/min)} & \leq 260.0 \\ & \text{Efficiency } \eta \text{ (\%)} & 95.03 \\ & \text{Reliability } \Gamma \text{ (\%)} & 92.00 \end{bmatrix}$$

$$J_{Turb\text{-}TA364\text{-}3} = \begin{bmatrix} \text{Runner } TA364\text{-}3 & \text{Nominal diameter } D_1 \text{ (m)} & 5.50 \\ & \text{Maximum height } H_1 \text{ (m)} & 3.217 \\ & \text{Design flow } Q_d \text{ (m}^3\text{/s)} & 348.00 \\ & \text{Rated rotation rate } n_r \text{ (r/min)} & 125.00 \\ & \text{Runaway rotation rate } n_R \text{ (r/min)} & \leq 250.0 \\ & \text{Efficiency } \eta \text{ (\%)} & 93.50 \\ & \text{Reliability } \Gamma \text{ (\%)} & 93.00 \end{bmatrix}$$

$$J_{Turb\text{-}TA364\text{-}4} = \begin{bmatrix} \text{Runner } TA364\text{-}4 & \text{Nominal diameter } D_1 \text{ (m)} & 5.734 \\ & \text{Maximum height } H_1 \text{ (m)} & 3.337 \\ & \text{Design flow } Q_d \text{ (m}^3\text{/s)} & 326.00 \\ & \text{Rated rotation rate } n_r \text{ (r/min)} & 136.40 \\ & \text{Runaway rotation rate } n_R \text{ (r/min)} & \leq 270.0 \\ & \text{Efficiency } \eta \text{ (\%)} & 94.00 \\ & \text{Reliability } \Gamma \text{ (\%)} & 93.00 \end{bmatrix}$$

Take efficiency and reliability as the main evaluation characteristics in the extension design of runner selection, and take the compact of structure type (that is, the diameter and height dimensions), runaway rotation rate, rated rotation rate, and rated flow as referenced evaluation characteristics, it can be seen that $\boldsymbol{J}_{Turb\text{-}TA364\text{-}1}$ is the best runner object of extension transform, that is:

$$\boldsymbol{J}_{Turb\text{-}best} = \boldsymbol{J}_{Turb\text{-}TA364\text{-}1} = \begin{bmatrix} \text{Runner } TA364\text{-}1 & \text{Nominal diameter } D_1 \text{ (m)} & 5.50 \\ & \text{Maximum height } H_1 \text{ (m)} & 2.92 \\ & \text{Design flow } Q_d \text{ (m}^3\text{/s)} & 307.00 \\ & \text{Rated rotation rate } n_r \text{ (r/min)} & 125.00 \\ & \text{Runaway rotation rate } n_R \text{ (r/min)} & \leq 260.0 \\ & \text{Efficiency } \eta \text{ (\%)} & 94.30 \\ & \text{Reliability } \Gamma \text{ (\%)} & 95.00 \end{bmatrix}$$

Because there is an extension implication relationship between runner $\boldsymbol{J}_{Turb\text{-}Runner04}$ and volute $\boldsymbol{J}_{\text{WK-94}} \mid A364$, draft tube $\boldsymbol{J}_{\text{WSG-51}} \mid A364$, guide vane $\boldsymbol{J}_{\text{DY-43}} \mid A364$, when carrying out extension transform for runner $\boldsymbol{J}_{Turb\text{-}Runner04}$'s characteristic value, the volute $\boldsymbol{J}_{\text{WK-94}} \mid A364$, draft tube $\boldsymbol{J}_{\text{WSG-51}} \mid A364$ and guide vane $\boldsymbol{J}_{\text{DY-43}} \mid A364$'s design requirement parameters would change. According to the comprehensive characteristic curve of the turbine runner, we can acquire the corresponding design requirement interval. Table 3 gives the design requirement parameters of the partial flow path model.

Table 3. The Design Requirement Parameters of Partial Flow Path Model.

The Name of Characteristic	The Value of Characteristic	The Name of Characteristic	The Value of Characteristic
The diameter of volute inlet side	6.200–7.800 (m)	The pitch circle diameter of guide vane	5.300–6.650 (m)
The thickness of the volute inlet side	35.000–65.000 (mm)	The height of the guide vane	1.000–1.560 (m)
The thickness of the end of volute	18.500–26.000 (mm)	The relative height of the guide vane	0.200–0.275
The weight of volute	140.000–180.000 (T)	The weight of the guide vane	1.650–2.820 (T)
The thickness of draft tube lining	15.000–18.500 (mm)	The weight of draft tube lining	15.700–21.100 (T)

For this, it needs to carry out volute, draft tube, and guide vane's extension configuration design and extension adaptive design based on the new design requirement parameters, and then complete the scheme design of large turbine selection. If carrying out extension configuration design and extension adaptive design, it needs to carry out weight allocation for every characteristic. Because extension configuration design is mainly too fast and extensible to match the design objects based on existing design instances or design results, so the influence of common requirement characteristics for the weight of every characteristic parameter is most prominent; for this, this paper takes common requirement characteristics as evaluation standards of the design characteristic parameters weight allocation. On the basis of the description in the paper, take common requirement characteristics of the head, output, efficiency, cavitation property, and runaway property as requirement basic element items, and take volute, draft tube, and guide vane as design parameter basic element items, invite six experts in the turbine design field to grade requirement basic element items and design parameter basic element items by ratio scale interval [1–9], the specific values are shown in Tables 4 and 5.

Table 4. The Scoring Results of Requirement Basic Element Items.

The Requirement Basic Element Item	The Scoring Result
head	([7.0, 8.0], [7.5, 8.0], [7.0, 8.0], [8.0, 8.5], [8.0, 9.0], [7.5, 8.0])
Output	([9.0, 9.0], [9.0, 9.0], [9.0, 9.0], [9.0, 9.0], [9.0, 9.0], [9.0, 9.0])
Efficiency	([7.5, 8.0], [8.0, 8.5], [8.0, 8.5], [7.5, 8.0], [7.5, 8.5], [8.0, 9.0])
Cavitation property	([6.0, 7.0], [6.5, 7.5], [6.0, 6.5], [7.0, 7.5], [7.5, 8.0], [7.0, 8.0])
Runaway property	([7.5, 8.0], [7.5, 8.0], [8.0, 9.0], [8.0, 8.5], [7.5, 8.0], [7.5, 8.0])

Table 5. The Scoring Results of Design Parameter Items.

The Design Parameter Item	The Scoring Result
Volute	([7.5, 8.0], [8.0, 8.5], [8.0, 8.5], [8.0, 8.5], [7.5, 8.0], [7.5, 8.0])
Draft tube	([7.5, 8.0], [8.0, 8.5], [7.0, 7.5], [8.0, 8.5], [7.0, 7.5], [7.5, 8.0])
Guide vane	([8.0, 8.5], [8.5, 9, 0], [8.0, 8.5], [8.0, 8.5], [8.5, 9.0], [8.5, 9.0])

Build requirement basic elements' ideal ratio scale interval sequence $U(0)$ = ([9, 9], [9, 9], [9, 9], [9, 9], [9, 9], [9, 9],), based on the Formula (7) build extension correlation coefficient matrix ρ between the requirement basic element items and requirement basic elements' ideal ratio scale interval sequence $U(0)$:

$$\boldsymbol{\rho} = \begin{bmatrix} 7.500 & 7.750 & 7.500 & 8.250 & 8.500 & 7.750 \\ 9.000 & 9.000 & 9.000 & 9.000 & 9.000 & 9.000 \\ 7.750 & 8.250 & 8.250 & 7.750 & 8.000 & 8.500 \\ 6.500 & 7.000 & 6.250 & 7.250 & 7.750 & 7.500 \\ 7.750 & 7.750 & 8.500 & 8.250 & 7.750 & 7.750 \end{bmatrix}$$

Build extension correlation sequence λ between the requirement basic element items and requirement basic elements' ideal ratio scale interval sequence $U(0)$ based on Formula (8):

$$\lambda = [7.875,\ 9.000,\ 8.083,\ 7.042,\ 7.958]^T$$

Acquire the weight sequence of requirement basic element items based on Formula (9):

$$w_U = [0.197,\ 0.226,\ 0.202,\ 0.176,\ 0.199]^T$$

For design parameters items, separately select requirement basic element items as ideal ratio scale interval sequence, acquire extension correlation degree matrix $\boldsymbol{A_J}$ between design parameters and requirement basic element items based on Formulas (10) and (11):

$$\boldsymbol{A_J} = \begin{bmatrix} 8.917 & 8.917 & 8.708 \\ 8.000 & 7.750 & 8.500 \\ 8.958 & 8.792 & 8.875 \\ 8.375 & 8.500 & 7.917 \\ 9.000 & 8.792 & 8.625 \end{bmatrix}$$

We can acquire the design parameters' weight sequence $w_V = [0.364, 0.321, 0.333]^T$ based on Formulas (12)–(14). By weight sequence, it can be seen that the weights of the various design parameters are consistent with turbine design because volute, draft tube, and guide vane are all the core components of each functional unit, so when carrying out fast configuration design, the weight of them is little difference; At the same time, due to the volute as diversion components, we should lead water into hydraulic components by minimum hydraulic losses and ensure water flow uniform, then it is conducive to the guiding apparatus that the guide vanes carry out flow regulation and draining parts that are draft tube carry out reflow processes, so the weight of volute is slightly higher.

In addition, as the volute, draft tube, and guide vane's design requirement parameters are all the key control parameters, so volute, draft tube, and guide vane's respective design attributes have the same weight; that is, the volute's respective design attributes weights are $w_{V\text{-}WK}$ = 0.250, draft tube's respective design attributes weights are $w_{V\text{-}WSG}$ = 0.500, guide vane's respective design attributes weights are $w_{V\text{-}DY}$ = 0.250.

5. Discussion

From the above theoretical discussion and application cases, it can be seen that the method proposed in this paper has a strong theoretical foundation. From the topological knowledge modeling, extension analysis, implication analysis, demand analysis index weight acquisition, and extension pattern generation in demand analysis, an extension demand analysis method system for complex product scheme design is formed, which has good engineering applicability.

By establishing the basic element model of complex product scheme design requirement information and the corresponding extension set of requirement basic elements, this method can formally represent various deep-seated design requirement information. This method establishes the extension process model of complex product scheme design requirement analysis and the implication process model of requirement analysis. Based on the inherent implication and relevance of design requirement information, the rapid transformation and hybrid reasoning of design requirements are carried out, which makes the mapping of complex product scheme design requirements more intuitive and effective. Moreover, this method gives a basic demand element weight distribution model based on extension distance, which can obtain accurate demand analysis weight from the combination of qualitative and quantitative perspectives and can take into account the influence of design constraints and design characteristics on the design demand attribute weight. At the same time, based on the extension correlation degree of basic demand elements, this paper establishes the implementation framework and algorithm of the extension design pattern for the demand analysis of complex product scheme design, which comprehensively reflects the design requirements and design intent of the scheme and provides support for the smooth implementation of complex product design. The application of the example also verifies the effectiveness and feasibility of the algorithm.

In addition, the application of knowledge extension reuse technology in complex product scheme design not only makes product design standardized and systematic but also expands the application field of expert systems, provides a theoretical basis for computer-aided product conceptual design, and plays an important role in the smooth implementation of complex product design scheme development.

6. Conclusions

In view of the multi-level, multi-attribute, and creative product structure configuration process of complex products, this paper studies and analyzes the extension design mode of complex product scheme design demand analysis with the characteristics of abstraction, fuzziness, variability, diversity, hierarchy, and relevance. The specific results and conclusions are as follows: (1) The basic element model of the demand information of complex product scheme design and the corresponding extension set of the basic demand element are established to realize the formal modeling of the demand analysis and design information of the product scheme design. (2) The extension process model and the implication process model of demand analysis for complex product scheme design are established, which provides support for generating more abundant knowledge of demand analysis. (3) The weight distribution model of the basic demand element based on extension distance is established, which provides support for improving the reasoning ability of product demand analysis. (4) The framework and algorithm of the extension design pattern for the requirement analysis of complex product scheme design are proposed, and the extension requirement analysis of complex product scheme design is realized. On the basis of obtaining the results of extension requirement analysis, how to effectively carry out extension knowledge reasoning and extension knowledge reuse of complex product scheme design will have important research significance, which will provide important support for rapid configuration design of complex products.

Author Contributions: Conceptualization, T.W.; Data curation, T.W.; Formal analysis, T.W., H.L. and X.W.; Funding acquisition, T.W.; Methodology, T.W.; Validation, H.L. and X.W.; Writing—original draft, T.W.; Writing—review & editing, T.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Natural Science Foundation of Jiangsu Province of China (No. BK20221481), the National Natural Science Foundation of China (No. 51775272, No. 51005114).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The labeled dataset used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Yi, Y.; Yan, Y.; Liu, X.; Ni, Z.; Feng, J.; Liu, J. Digital twin-based smart assembly process design and application framework for complex products and its case study. *J. Manuf. Syst.* **2021**, *58*, 94–107. [CrossRef]
2. Delaram, J.; Houshamand, M.; Ashtiani, F.; Valilai, O.F. A utility-based matching mechanism for stable and optimal resource allocation in cloud manufacturing platforms using deferred acceptance algorithm. *J. Manuf. Syst.* **2021**, *60*, 569–584. [CrossRef]
3. Zhang, L.; Zhou, L.; Ren, L.; Laili, Y. Modeling and simulation in intelligent manufacturing. *Comput. Ind.* **2019**, *112*, 103123. [CrossRef]
4. Tao, Y.; Meng, K.; Lou, P.; Peng, X.; Qian, X. Joint decision-making on automated disassembly system scheme selection and recovery route assignment using multi-objective meta-heuristic algorithm. *Int. J. Prod. Res.* **2019**, *57*, 124–142. [CrossRef]
5. Liu, F.; Zhang, Y.; Zheng, C.; Qin, X.; Eynard, B. Survey of Configuration Design Approaches: A Focus on Design of Complex Industrial Manufacturing Systems. *Procedia CIRP* **2019**, *81*, 340–345. [CrossRef]
6. Shabestari, S.S.; Bender, B.; Neumann, M.; Song, Y. Decision support for Design Conflicts: A model-based method to analyze the interactions between technical requirements and product characteristics. *Procedia Manuf.* **2020**, *52*, 203–208. [CrossRef]
7. Xiuli, G.E.N.G.; Shidong, X.U.; Chunming, Y.E. Optimal design method of product function requirements considering quantitative KANO analysis. *Comput. Integr. Manuf. Syst.* **2016**, *22*, 1645–1653.
8. Lee, C.; Chen, C.; Lee, Y. Customer requirement-driven design method and computer-aided design system for supporting service innovation conceptualization handling. *Adv. Eng. Inform.* **2020**, *45*, 101117. [CrossRef]
9. Silva, J.M.; Silva, J.R. A new hierarchical approach to requirement analysis of problems in automated planning. *Eng. Appl. Artif. Intell.* **2019**, *81*, 373–386. [CrossRef]
10. Geng, X.; Ye, C. Importance weights determination of based on feature selection customer requirements technique. *Comput. Integr. Manuf. Syst.* **2014**, *20*, 1751–1757.
11. Li, Y.; Chen, H.; Zhao, Z. An integrated identification approach of agile engineering characteristics considering sensitive customer requirements. *CIRP J. Manuf. Sci. Technol.* **2021**, *35*, 13–24. [CrossRef]
12. Zhang, J.; Qiao, L.; Rao, P.; Wulan, M. Product Requirement Information Modeling for the Life Cycle of the Port Hoisting Equipment. *Procedia CIRP* **2016**, *56*, 79–83. [CrossRef]
13. Wei, W.; Liu, A.; Lu, S.C.-Y.; Wuest, T. Product Requirement Modeling and Optimization Method Based on Product Configuration Design. *Procedia CIRP* **2015**, *36*, 1–5. [CrossRef]
14. Dong, C.; Yang, Y.; Chen, Q.; Wu, Z. A complex network-based response method for changes in customer requirements for design processes of complex mechanical products. *Expert Syst. Appl.* **2022**, *19*, 117124. [CrossRef]
15. Wang, T.; Wang, J. A fault diagnosis model based on weighted extension neural network for turbo-generator sets on small samples with noise. *Chin. J. Aeronaut.* **2020**, *33*, 2757–2769. [CrossRef]
16. Ma, L.; Chen, H.; Yan, H.; Li, W.; Zhang, J.; Zhang, W. Post evaluation of distributed energy generation combining the attribute hierarchical model and matter-element extension theory. *J. Clean. Prod.* **2018**, *184*, 503–510. [CrossRef]
17. Zhou, Y.; Shi, J.; Wu, L. Application of Extension Theory in Emotion Management. *Procedia Comput. Sci.* **2017**, *122*, 502–509. [CrossRef]
18. Ren, J. Technology selection for ballast water treatment by multi-stakeholders: A multi-attribute decision analysis approach based on the combined weights and extension theory. *Chemosphere* **2018**, *191*, 747–760. [CrossRef]
19. Tao, W.; Qingying, H.; Dongsheng, W.; Adeyeye, K.; Peng, Y. Extension Theory for the Reconstruction of Traditional Villages: Case example in Dawa Village. *Procedia Comput. Sci.* **2019**, *162*, 191–198. [CrossRef]

20. Wang, W.; Wang, H.; Zhang, B.; Wang, S.; Xing, W. Coal and gas outburst prediction model based on extension theory and its application. *Process Saf. Environ. Prot.* **2021**, *154*, 329–337. [CrossRef]
21. Zhang, X.; Yue, J. Measurement Model and its Application of Enterprise Innovation Capability Based on Matter Element Extension Theory. *Procedia Eng.* **2017**, *174*, 275–280. [CrossRef]
22. Wang, J.; Guo, H.; Chen, J. Research on Extension Innovation Model in the Creation Process of Service Design. *Procedia Comput. Sci.* **2022**, *199*, 992–999. [CrossRef]
23. Du, Y.; Zheng, Y.; Wu, G.; Tang, Y. Decision-making method of heavy-duty machine tool remanufacturing based on AHP-entropy weight and extension theory. *J. Clean. Prod.* **2020**, *252*, 119607. [CrossRef]
24. Kulak, O.; Cebi, S.; Kahraman, C. Applications of axiomatic design principles: A literature review. *Expert Syst. Appl.* **2010**, *37*, 6705–6717. [CrossRef]
25. Houshmand, M.; Jamshidnezhad, B. An extended model of design process of lean production systems by means of process variables. *Robot. Comput.-Integr. Manuf.* **2006**, *22*, 1–16. [CrossRef]
26. Delaram, J.; Valilai, O.F. An architectural view to computer integrated manufacturing systems based on Axiomatic Design Theory. *Comput. Ind.* **2018**, *100*, 96–114. [CrossRef]
27. Fan, L.X.; Cai, M.Y.; Lin, Y.; Zhang, W.J. Axiomatic design theory: Further notes and its guideline to applications. *Int. J. Mater. Prod. Technol.* **2015**, *51*, 359–374. [CrossRef]
28. Liu, F.; Niu, B.; Xing, M.; Wu, L.; Feng, Y. Optimal cross-trained worker assignment for a hybrid seru production system to minimize makespan and workload imbalance. *Comput. Ind. Eng.* **2021**, *160*, 107552. [CrossRef]
29. Fan, X.; Weng, J. Tabu-search-based order seat planning for engineer-to-order manufacturing. *Asian J. Manag. Sci. Appl.* **2020**, *5*, 160–180. [CrossRef]
30. Cross, N. *Engineering Design Methods: Strategies for Product Design*; John Wiley & Sons: Hoboken, NJ, USA, 2008.
31. Daalhuizen, J.; Cash, P. Method content theory: Towards a new understanding of methods in design. *Des. Stud.* **2021**, *75*, 101018. [CrossRef]
32. Harding, J.E.; Shepherd, P. Meta-Parametric Design. *Des. Stud.* **2017**, *52*, 73–95. [CrossRef]
33. Osiński, P.; Deptuła, A.; Partyka, M.A. Discrete optimization of a gear pump after tooth root undercutting by means of multi—Valued logic trees. *Arch. Civ. Mech. Eng.* **2013**, *13*, 422–431. [CrossRef]
34. Yang, W.; Cao, G.; Peng, Q.; Sun, Y. Effective radical innovations using integrated QFD and TRIZ. *Comput. Ind. Eng.* **2021**, *162*, 107716. [CrossRef]
35. Rampal, A.; Mehra, A.; Singh, R.; Yadav, A.; Nath, K.; Chauhan, A.S. Kano and QFD analyses for autonomous electric car: Design for enhancing customer contentment. *Mater. Today Proc.* **2022**, *62*, 1481–1488. [CrossRef]