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Research Article

Research on Designing an Industrial Product-Service System with Uncertain Customer Demands

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The industrial product-service system (iPSS) is a kind of system engineering methodology, integration scheme, and business model to realize service value by adding intangible services in the whole life cycle. However, the design of the system involves many difficulties such as uncertain customer demands, strong subjectivity of the experience design, and long debugging times. Methods for solving upper problems are therefore essential. This paper presents a design model that integrates an improved affinity propagation (AP) clustering algorithm, quality function development (QFD), and axiomatic design (AD). The entire process of designing an iPSS can be split into three steps. First, uncertain customer demands is determined and standardized. Second, the functions of the product-service system are investigated. Finally, the structures of the system are determined. This paper examines the example of the control service of an iPSS for a water heater tank capping press. An improved AP clustering algorithm is used to determine standardized customer demands, the proposed QFD, and an AD integration model to initially establish a mapping between the customer demands domain and the function domain and clarify the design focus. Next, a QFD- and AD-integrated model is constructed to establish a mapping between the function domain and the structure domain and optimize the control scheme through the quality of its risk prediction. Finally the paper verifies that the upper process and methods can guide the design process effectively in production applications.

1. Introduction

The Made in China 2025 policy lists intelligent manufacturing as one of China's five key projects and presents a comprehensive plan to develop the intelligent manufacturing industry [1]. In 2006, the Weishang factory cooperated with Yuanfang Software Company to carry out the first furniture informatization renovation in China, and in 2016, it was awarded as the only smart manufacturing demonstration base in the home furnishing industry [2]. At the same time, Sinopec Jiujiang Branch integrated modern information technology and established a digital monitoring and optimization system, covering the entire process of "management, production, operation, and warehousing," becoming a sample of intelligent transformation of process-oriented manufacturing [3]. Zhejiang Toman Machinery Co., Ltd. introduced intelligent manufacturing technology in 2013 to improve product quality and production efficiency. Since 2014, Toman has used self-developed systems to provide SMEs (small and medium-sized enterprises) with customized solutions, such as TM-e (a production management system) and TM-SPC (a quality control system). Toman has transformed from an equipment manufacturer to a production system integrator [4]. With the continuous development of intelligent manufacturing in practice, a variety of different themes have emerged. These themes include the Internet of things [5], big data manufacturing [6], cloud manufacturing [7], and digital twin [8], which play a positive role in guiding the technological upgrading of the manufacturing industry. For example, Jiang et al. [9–11] developed a new MATLAB toolbox, the data-based key performance indicator-oriented fault detection toolbox

(DB-KIT), for evaluating the influence of the detected faults on systems behavior, reviewed the key scientific issues in the design and implementation of soft sensors in modern industry, and also proposed a research route centered on the construction of performance evaluation system and performance-oriented fault diagnosis methods. Su and Yu [12] constructed a spatial econometric model with geographical proximity as the spatial weight to study the effect of spatial agglomeration of new energy industries on regional pollution control performance. The development of the intelligent manufacturing industry has driven the rapid development of the industrial product-service system (iPSS) in China. Zhu et al. [13] comprehensively considered processing time, cost, and quality and proposed a machining capability model for quantifying and measuring machining capabilities of an mt-iPSS (industrial product-service system of a machine tool). Based on the tool-based industrial product-service system, Sun et al. [14] further studied the tool delivery method in the iPSS, established a cutting tool demand prediction model and a tool delivery model, and proposed a novel cutting tool service model. Ding et al. [15] discussed the multiobjective resource scheduling problem in the operation phase of iPSS, used an improved NSGA-II algorithm to solve the multiobjective problem including comprehensive customer satisfaction degree, resource utilization efficiency, and product-service cost, and verified the feasibility with a case of China Yufeng Electric Power Company. Leng et al. [16] proposed the concept of a cost-effective industrial product-service system for oil sands mining (om-iPSS). Haeberle et al. [17] proposed a method of systematically establishing service parameters to enhance the effectiveness of industrial service systems for establishing new services. However, there is no analysis and research on how the service parameters can be obtained from customer needs. Industrial electronic control systems constitute the control core of the iPSS of complete equipment. Usually, the control system's design is based on customer demands. The designer creates a control system's software and hardware design based on personal experience and professional knowledge. However, this design method is inadequate. First, customers are restricted by the professional's knowledge and resource conditions, customers' demands are often unclear and hard to determine, and the method involves too many ambiguities and uncertainties. Second, designers have different levels of experience and lack scientific theory to guide the design process. Therefore, when customer demands are uncertain, it is difficult for the designer to deliver a good product/service. It is, therefore, critical that the iPSS of complete equipment be provided with accurate information about customer demands to quickly design a satisfactory control system.

Quality function deployment (QFD) and axiomatic design (AD) are product design methods driven by customer demand that have been widely used in other product design fields. For example, Chang et al. [18] applied QFD theory to electric vehicles and provided an effective and scientific development tool for electric vehicle manufacturers. Wang et al. [19] used QFD theory to solve a multiobjective decision problem in a collaborative supply chain network. Han et al. [20] applied QFD theory to the field of augmented reality design, achieving collaborative customer innovation and improving customer satisfaction. Avikal et al. [21] constructed a new method based on the fuzzy Kano model and QFD theory for designing the exterior of a sport utility vehicle. The project QFD tool developed by Chao et al. [22] was used by an electronics company in Japan to engage in semiconductor projects and business model development to help deploy solution elements and resources. Vinodh et al. [23] considered environmental factors at various stages of QFD and proposed the QFDE method, which was applied to the Indian rotary switch manufacturing organization to achieve an environmentally conscious design in the early stages of product development. The SOFRAGRAF Company used QFD for the design of hand tools, staplers, nailing machines, etc. [24] In addition, QFD was used to design university textbooks and improve the quality of courses. Rainstar University in Scottsdale, Arizona, applied QFD to the redesign of higher education courses. [25] Liu et al. [26] established a conceptual design process model by applying the theory of inventive problem solving and AD to the innovative design of the manipulator. Tamayo et al. [27] combined AD and a design structure matrix to determine customer demands at the conceptual design stage of a manufacturing system. Goo et al. [28] introduced independence and failure modes in AD to improve the reliability of the product design process. Pétursson et al. [29] used AD to complete the research and development of shape-memory alloy spring static test equipment. Bae et al. [30] used independent axioms to define the relationship between hard points and suspension geometries and improve suspension system design and proposed a sequential kinematics design of suspension system based on the axiomatic design (AD). Lo and Helander [31] developed a method based on AD to identify couplings and make recommendations to eliminate couplings. This method was applied to the design of adjustable microscope workstations and the design of manual SLR (single-lens-reflex) cameras. Durmusoglu and Kulak [32] developed a method of designing efficient office operations using AD principles, which improves office operations and enhances business competitiveness by reducing customer delivery times. Ferrer et al. [33] proposed a two-stage method based on the AD method to define the structure of manufacturing knowledge and develop a knowledge-based DFM (Design for Manufacturing) application for connecting rod and internal combustion engine parts' design.

Given this background, QFD can clearly define the design focus of a product-service system, and the importance of customer demands can be transmitted by the house of quality (HoQ). However, QFD is based on an empirical design and lacks objective criteria; therefore, it is impossible to verify the rationality of the design process [34]. AD provides a set of scientific design methods and axioms that can verify this rationality, but there are no effective means to map between the customer demand domain and the function domain, and the design's emphasis cannot be clearly defined. This paper, therefore, introduces a new method integrated with AP, QFD, and AD to design a control system for the iPSS of complete equipment.

As shown in Figure 1, the design model starts with an analysis of customer demands. It then uses an improved AP clustering algorithm to complete the cluster analysis of the original customer demands information. Next, it establishes a system for the functional HoQ to complete the mapping between the demand domain and the function domain. Finally, following AD theory, the function domain is mapped to the structure domain. Moreover, based on this, risk prediction of the HoQ is established to optimize the system structure. The proposed QFD and an AD integration model initially establish a mapping between the customer demand domain and the function domain and clarify the design focus.

Moreover, in view of the vagueness, dispersion, and uncertainty of customer demands obtained from interviews and questionnaires, this paper proposes an AP clustering algorithm based on a weighted network. The algorithm uses an intuitionistic fuzzy decision matrix to quantify the correlation between demand nodes, uses a weighted network to determine the distribution density of demand nodes, and then determines the selection of initial deviation parameters P.

This paper will take the control service design of an iPSS for a water heater tank capping press as example. The improved AP clustering algorithm will be used to determine standardized customer demands. Then the QFD and an AD integration model will be used to initially establish a mapping between the customer demand domain and the function domain and clarify the design focus. Finally, a QFD- and AD-integrated model will be constructed to establish a mapping between the function domain and the structure domain and optimize the control scheme through the quality of its risk prediction.

2. Cluster Analysis of Customer Demands

QFD and AD are driven by customer demands; thus, the accuracy of these demands is very important. Fuzzy or uncertain customer demands will affect the rationality and accuracy of the subsequent design process. However, due to limitations in professional knowledge, resource conditions, and so on, customers' requirement descriptions have certain ambiguities and uncertainties. Therefore, to standardize customer demands, this paper proposes an AP clustering algorithm based on a weighted network for a cluster analysis of customer demands.

2.1. AP Clustering Algorithm Based on a Weighted Network. The basic idea of an AP clustering algorithm is to use all the data points as potential clustering centers and perform clustering on a similarity matrix of the data points [35]. The AP clustering algorithm has yielded good results in applications such as image processing, community detection, and fault diagnosis because of its strong clustering stability and lack of predefined information [36, 37]. Zhang proposed an improved K-means algorithm and an improved AP clustering algorithm to determine the modular configuration of service elements [38, 39]. However, research on the AP clustering algorithm in the processing of customer demand information is still lacking.

In the AP clustering algorithm, responsibility $r(i, k)$ and availability $a(i, k)$ represent two types of data object information [40]. As shown in Figure 2, $r(i, k)$ describes the suitability of data object k as the clustering center of data object i. It also represents the message from i to k. The term $A(i, k)$ describes the suitability of data object i as the clustering center of data object k. It also represents the message from k to i. At the end of the affinity propagation, the class representative point x_i is determined to be x_k, where k satisfies

$$\arg_k \min(a(i,k) + r(i,k)). \tag{1}$$

The iterative process of the AP algorithm involves alternating the updates of two information sources. As shown in the following equation, when the sum of the $r(i, k)$ and $a(i, k)$ values of all the data points for any x_i is calculated, the representative point of the class of x_i is x_k:

$$r(i,k) + a(i,k) = s(i,k) + a(i,k) - \max_{k' \neq k}\left[a\left(i,k'\right) + s\left(i,k'\right)\right]. \tag{2}$$

The AP algorithm refers to the message transmission of data points. Normally, a sample's representativeness can be determined by its reliability and validity. If the change value of $a(i, k)$ and $r(i, k)$ is the highest, then k_x is a representative sample of i_x. When the local $a(i, k)$ and $r(i, k)$ values no longer change, messaging will stop [41].

Additionally, the AP clustering algorithm introduces a damping factor λ and a deviation parameter P. The factor λ has a value range [0, 1] and is used to adjust the convergence rate of the algorithm and the stability of the iterative process. Generally, $\lambda = 0.5$ is selected. When the iterative process has large oscillations, the value of λ can be accordingly reduced or increased. The parameter P has a value range [0, 1], which is the criterion for a data point i becoming a cluster center. The larger the value, the greater the probability of the point becoming a cluster center, and vice versa. When P is less than or greater than a certain threshold, the number of clusters will change [42]. Therefore, the AP clustering algorithm has certain limitations in terms of the initial bias [43].

The steps of the AP clustering algorithm are as follows [44, 45].

Step 1: use the Euclidean distance between data points i and j to calculate the similarity $s(i, j)$:

$$s(i,j) = -x_i - x_j^2, \quad i \neq j. \tag{3}$$

Step 2: assign an initial preference to each data point in the sample, where the value range of P is [0, 1].

Step 3: calculate $r(i, k)$, such that

$$r(i,k) \leftarrow s(i,k) - \max_{j \neq k}[s(i,j) + a(i,j)]. \tag{4}$$

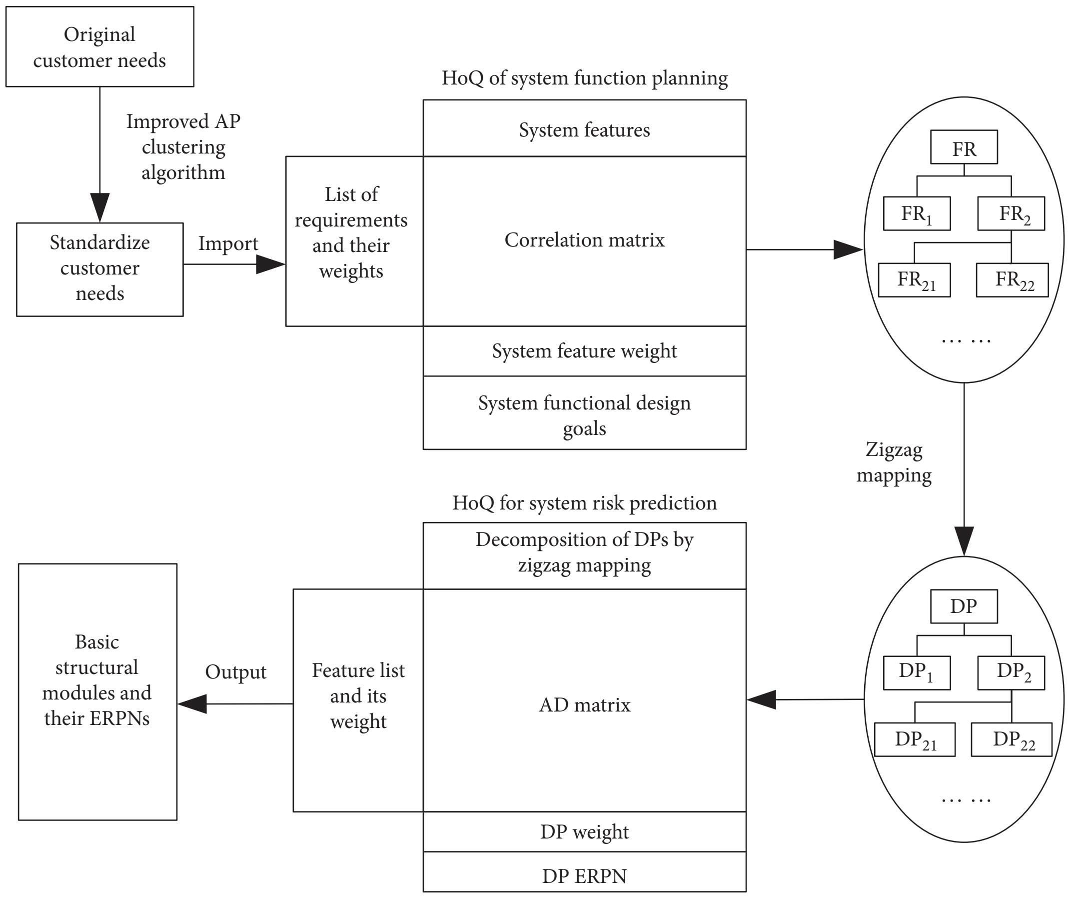


Figure 1: Design model integrating AP/QFD/AD, with functional requirements (FR), design parameters (DPs), and extended risk priority numbers (ERPNs).

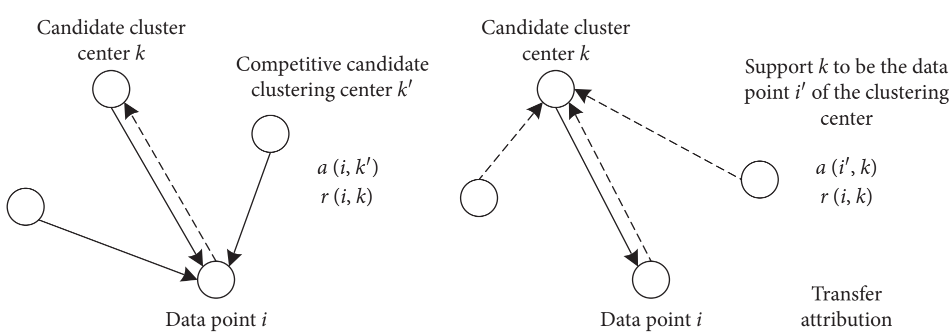


Figure 2: AP clustering algorithm message transmission.

Step 4: calculate $a(i, k)$, such that

$$a(i,k) \leftarrow \min\left\{0, r(k,k) + \sum_{j \neq i,k} \max[0, r(j,k)]\right\}, \tag{5}$$

$$a(k,k) \leftarrow \sum_{j \neq k} \max[0, r(j,k)]. \tag{6}$$

Step 5: update $r(i, k)$ and $a(i, k)$, respectively, according to

$$r_{i+1}(i,k) = \lambda \cdot r_i(i,k) + (1-\lambda) \cdot r_{i+1}^{ok_1}, \quad \lambda \in [0.5, 1], \tag{7}$$

$$a_{i+1}(i,k) = \lambda \cdot a_i(i,k) + (1-\lambda) \cdot a_{i+1}^{ok_1}(i,k), \quad \lambda \in [0.5, 1]. \tag{8}$$

Step 6: if the number of iterations exceeds the maximum value or the number of consecutive iterations of the cluster center no longer changes, the calculation is stopped; otherwise, go to Step 3 to continue the calculation.

According to the implementation steps of the AP clustering algorithm, two problems arise in the clustering of customer demands. The first is that the AP clustering algorithm uses the Euclidean distance to calculate the distance between two data points. The weight of each data point to the distance is the same by default, so the construction of the similarity matrix cannot truly reflect the correlation of the demands [46]. The second problem is that the initial P value is set manually, and the probability of each data point being a clustering center is the same, by default, which is obviously unreasonable.

Considering these two problems, this paper introduces a weighted network AP clustering algorithm for the cluster analysis of customer demands. This method uses intuitionistic fuzzy sets to transform the correlation of demands into quantized data to construct a weighted complex network and a weighted network model of customer demands to determine the initial P value.

Atanassov proposed the intuitionistic fuzzy set [47]. A weighted network can be used to describe complex correlations of nodes. It can clearly describe the interaction strengths of individuals, where the weights represent the connection tightness of the nodes in the network [44]. In a weighted network, $V = \{v_1, v_2, \ldots, v_n\}$ represents the set of nodes, (v_i, v_{ij}) represents the undirected edge between nodes v_{ii} and v_{ij}, and $E \in \{(v_{ii}, v_{ij}) : v_{ii}, v_{ij} \in V\}$ is the undirected edge set. The term w_{ij} represents the weight of the undirected edge (v_i, v_j), and $W = \{w_{ij} : (v_i, v_j) \in E\}$ is the weight set.

In a weighted network, the weights of the nodes reflect the interrelations and importance of each node in the network. The interaction strengths of the nodes are measured by the weights of the edges. In addition, the weights of the edges are related not only to directly connected nodes but also to neighboring nodes. Generally, the higher the number of neighboring nodes, the greater the strength of the interactions of the nodes [48]. Therefore, a weighted network used to analyze the distribution density of customer demand nodes should consider not just one factor, but all other relevant factors as well. In the customer demand-weighted network model, five basic indicators reflect the connection density around the demand nodes [49, 50], as shown in Table 1.

According to the basic principles of an AP clustering algorithm based on a weighted network, the nodes are the customer demand units, the edges represent the correlations of the demand units, and the weights of the edges represent the similarities of the demand units. An undirected weighted network model of customer demand can thus be established. Therefore, the subjective influence of an initial deviation parameter determined by local density can be avoided in the AP clustering algorithm. The entire process can be described as follows:

Step 1: construct an intuitionistic fuzzy decision matrix. Let CR_i and CR_j be any two customer demands. The decision maker evaluates the similarity u_{ij} and dissimilarity v_{ij} between CR_i and CR_j according to the intuitive fuzzy evaluation scale. The evaluation ranges of u_{ij} and v_{ij} are both [0, 1], and $0 \le u_{ij} + v_{ij} \le 1$. Then, the decision maker's intuitionistic fuzzy decision matrix Z for n demands is

$$Z = \left(d_{ij}\right)_{n\times n} = \left\{ \begin{array}{cccc} (u_{11}, v_{11}) & (u_{12}, v_{12}) & \ldots & (u_{1j}, v_{1j}) \\ (u_{21}, v_{21}) & (u_{22}, v_{22}) & \ldots & (u_{2j}, v_{2j}) \\ \vdots & \vdots & \ldots & \vdots \\ (u_{i1}, v_{i1}) & (u_{i2}, v_{i2}) & \ldots & (u_{nn}, v_{nn}) \end{array} \right\}, \tag{9}$$

where the intuitionistic fuzzy number $d_{ij} = <u_{ij}, v_{ij}>$.

Step 2: solve the intuitionistic fuzzy similarity matrix. Let the intuitive fuzzy evaluation value between CR_i and CR_j be $d_{ij} = <u_{ij}, v_{ij}>$. The similarity, dissimilarity, and hesitancy distances between CR_i and CR_j, respectively, are as follows.

Similarity distance:

$$d_1(a_i, a_k) = \sqrt[2]{\sum_{j=1}^{n}\left(u_{ij} - u_{kj}\right)^2}. \tag{10}$$

Dissimilarity distance:

$$d_2(a_i, a_k) = \sqrt[2]{\sum_{j=1}^{n}\left(v_{ij} - v_{kj}\right)^2}. \tag{11}$$

Hesitation distance:

$$d_3(a_i, a_k) = \sqrt[2]{\sum_{j=1}^{n}\left(\pi_{ij} - \pi_{kj}\right)^2}. \tag{12}$$

The intuitive fuzzy similarity of a_i and a_k is described byρ $(a_i, a_k) = <\alpha_{ij}, \beta_{ij}> = <1 - d_1 (a_i, a_k) - d_3 (a_i, a_k), d_2 (a_i, a_k)>$:

$$D = \left(\rho_{ij}\right)_{n\times n} = \begin{bmatrix} \rho_{11} & \rho_{12} & \cdots & \rho_{1j} \\ \rho_{21} & \rho_{22} & \cdots & \rho_{2j} \\ \vdots & \vdots & \ldots & \vdots \\ \rho_{i1} & \rho_{i2} & \cdots & \rho_{nn} \end{bmatrix}. \tag{13}$$

Step 3: convert the intuitionistic fuzzy similarity matrix into a real matrix:

$$F = \left(f_{ij}\right)_{n\times n} = \alpha_{ij} + \eta\left(1 - \alpha_{ij} - \beta_{ij}\right), \tag{14}$$

where η is the satisfaction threshold, $\eta \in [0, 1]$, such that

Table 1: Weighted network indicators.

Indicators	Definition
Connectivity	Number of edges to which a node is directly connected in a weighted network
Weighted degree	Sum of the weights of all edges directly connected to nodes in a weighted network
Weighted aggregation	Degree of aggregation around a node in a weighted network
Agglomeration coefficient	Degree of connection between a node and its neighbors in a weighted network
Weighted network comprehensive eigenvalues	Local distribution density around a node in a weighted network

$$F = \left(f_{ij}\right)_{n\times n} = \begin{bmatrix} f_{11} & f_{12} & \cdots & f_{1j} \\ f_{21} & f_{22} & \cdots & f_{2j} \\ \vdots & \vdots & \cdots & \vdots \\ f_{i1} & f_{i2} & \cdots & f_{nn} \end{bmatrix}. \quad (15)$$

Step 4: use the demand units as the nodes, the correlations of the demand units as the edges in the weighted network, and the similarities of the demand units as the weights of the edges to establish an undirected weighted network model of customer demands.

Step 5: calculate the connectivity, weighted degree, weighted aggregation, clustering coefficient, and weighted network comprehensive eigenvalues of the nodes, respectively:

$$D_i = \left|\left\{\left(v_i, v_j\right): \left(v_i, v_j\right) \in E, v_i, v_j \in V\right\}\right|, \quad (16)$$

where D_i represents the connectivity of node i;

$$\mathrm{WD}_i = \sum_{\left(v_i,v_j\right)\in E} w_{ij}, \quad (17)$$

where WD_i represents the weighted degree of node i;

$$\mathrm{WK}_i = \sum_{\left(v_j,v_k\in R\right)} w_{jk}, \quad (18)$$

where WK_i represents the weighted aggregation degree of node i, with $R = \{(v_j, v_k): (v_i, v_j) \in E, (v_i, v_k) \in E, (v_i, v_k) \in E, v_i, v_j, v_k \in V\}$;

$$\mathrm{WC}_i = \frac{2\mathrm{WK}_i}{\mathrm{WD}_i\left(\mathrm{WD}_i - 1\right)}, \quad (19)$$

where WC_i represents the aggregation coefficient of node i; and

$$\mathrm{WF}_i = \beta \mathrm{WC}_i + \frac{(1-\eta)\mathrm{WD}_i}{n}, \quad (20)$$

where WF_i represents the weighted network's comprehensive eigenvalue of node i, with β taking the value range of $[0, 1]$ and n as the total number of nodes in the weighted network. Finally, by normalizing the integrated eigenvalues of the weighted network of nodes, the initial P of each demand is determined.

Step 6: update the attraction and attribution values utilizing equations (4) to (8) until the stop condition is satisfied.

2.2. Cluster Analysis of Customer Demands for a Control Service System. To analyze customer demands, the example of a control service system for an iPSS for a water heater tank capping press is used. The capping press is for an enamel water tank liner of an air energy water heater, and it automatically presses the inner barrel and top cover in different diameters and lengths. The process flow diagram is depicted in Figure 3. The equipment uses a programmable logic controller (PLC) as the control core, an ABB robot as the top cover automatic feeding device, and a touch screen as the human-computer interaction interface.

The determination of customer demands can be divided into two stages. The first is the interview stage. When the water heater manufacturer purchases equipment, the designer obtains the customer's product and technical service demands by communicating with the customer group responsible for the purchase. After the interview, the questionnaire stage will be conducted. Use questionnaires to further obtain the use demands of maintenance personnel and operators.

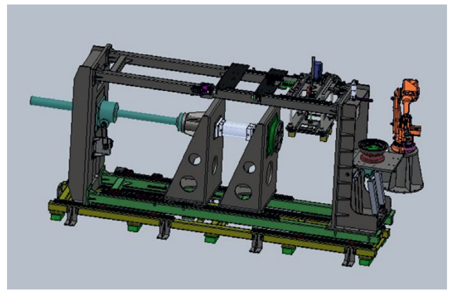
Finally, the customers' demands for a control service system are categories into 35 types, as shown in Table 2.

Furthermore, these customer demands can be clustered into subject categories. The design teams evaluate the similarity and dissimilarity of the demand units, and the evaluation results can be averaged, as shown in Table 3.

According to equations (10) to (14), the intuitionistic fuzzy similarity matrix D can be calculated as follows:

$$D = \begin{bmatrix} 1 & 0.243 & 0.102 & 0.097 & \ldots & 0.203 & 0.312 & 0.134 & 0.114 \\ 0.243 & 1 & 0.741 & 0.183 & \ldots & 0.302 & 0.241 & 0.177 & 0.715 \\ 0.102 & 0.741 & 1 & 0.162 & \ldots & 0.226 & 0.172 & 0.305 & 0.697 \\ 0.097 & 0.183 & 0.162 & 1 & \ldots & 0.152 & 0.181 & 0.629 & 0.407 \\ 0.203 & 0.302 & 0.226 & 0.152 & \ldots & 1 & 0.189 & 0.275 & 0.223 \\ 0.312 & 0.241 & 0.172 & 0.181 & \ldots & 0.189 & 1 & 0.096 & 0.164 \\ \vdots & \vdots & \vdots & \vdots & \ldots & \vdots & \vdots & \vdots & \vdots \\ 0.134 & 0.177 & 0.305 & 0.629 & \ldots & 0.275 & 0.096 & 1 & 0.304 \\ 0.114 & 0.715 & 0.697 & 0.407 & \ldots & 0.223 & 0.164 & 0.304 & 1 \end{bmatrix}. \quad (21)$$

In the weighted network, the demand units are represented by the nodes, the correlations of the demand units are represented by the edges, and the similarities of the demand units are represented by the weights of the edges. An undirected weighted network model of customer demand can be built by selecting the Force Atlas layout in the Gephi software, as shown in Figure 4.



(a) (b)

Figure 3: The capping press process.

Table 2: Customer demands for a control service system.

Number	Name	Number	Name
Cr_1	Information storage	Cr_{19}	Reset prompt
Cr_2	Parameter settings	Cr_{20}	Operation monitoring
Cr_3	Boot operation	Cr_{21}	Information query
Cr_4	Error alarm	Cr_{22}	Maintenance cost
Cr_5	Accident details	Cr_{23}	Graphical button size
Cr_6	Workpiece information	Cr_{24}	Picture color
Cr_7	Economical	Cr_{25}	Failure machine stop
Cr_8	Button layout	Cr_{26}	Line label
Cr_9	Selection error prompt	Cr_{27}	System upgrade
Cr_{10}	Part stability	Cr_{28}	Program structure
Cr_{11}	Part species	Cr_{29}	Program modification
Cr_{12}	Full features	Cr_{30}	Part replacement
Cr_{13}	Login authentication	Cr_{31}	Consistency check
Cr_{14}	Three levels of login authority	Cr_{32}	Clear interface marking
Cr_{15}	Operability	Cr_{33}	Equipment parameter query
Cr_{16}	Intensity	Cr_{34}	Operation feedback
Cr_{17}	Model switching	Cr_{35}	Error reset
Cr_{18}	Error self-diagnosis	—	—

Table 3: Customer demands: evaluation results.

	Cr_1	Cr_2	Cr_3	...	Cr_{33}	Cr_{34}	Cr_{35}
Cr_1	(1, 0)	(0.23, 0.72)	(0.12, 0.76)	...	(0.32, 058)	(0.16, 0.67)	(0.10, 0.82)
Cr_2	(0.23, 0.72)	(1, 0)	(0.71, 0.16)	...	(0.26, 0.60)	(0.18, 0.69)	(0.75, 0.12)
Cr_3	(0.12, 0.76)	(0.71, 0.16)	(1, 0)	...	(0.12, 0.69)	(0.34, 0.58)	(0.67, 0.18)
Cr_4	(0.08, 0.82)	(0.23, 0.59)	(0.12, 0.80)	...	(0.12, 0.72)	(0.69, 0.23)	(0.40, 0.48)
...	...	...	...	...	...	...	...
Cr_{32}	(0.18, 0.67)	(0.32, 0.59)	(0.24, 0.71)	...	(0.19, 0.68)	(0.28, 0.64)	(0.22, 0.58)
Cr_{33}	(0.32, 058)	(0.26, 0.60)	(0.12, 0.69)	...	(1, 0)	(0.09, 0.72)	(0.15, 0.69)
Cr_{34}	(0.16, 0.67)	(0.18, 0.69)	(0.34, 0.58)	...	(0.09, 0.72)	(1, 0)	(0.31, 0.64)
Cr_{35}	(0.10, 0.82)	(0.75, 0.12)	(0.67, 0.18)	...	(0.22, 0.58)	(0.31, 0.64)	(1, 0)

In the undirected weighted network model of customer demand, the parameter β is 0.5 according to equations (16) to (20). The calculation of the network attribute value of every node is shown in Table 4.

Since the range of the initial P value in the AP clustering algorithm is [0, 1], the initial P value of the customer requirements Cr_1, Cr_2, ..., Cr_{35} can be assumed to be $p_1, p_2, \ldots, p_{35}$. By adopting the normalization method to process the weighted network's comprehensive feature value of each node, the initial P value of every customer demand can be obtained, as shown in Table 5.

To facilitate calculation and programming, 35 random coordinate points are set to correspond to customer demands Cr_1, Cr_2, ..., Cr_{35}. The values of the initial deviation parameters for every demand are shown in Table 5, where the maximum number of iterations is set to 500 and the

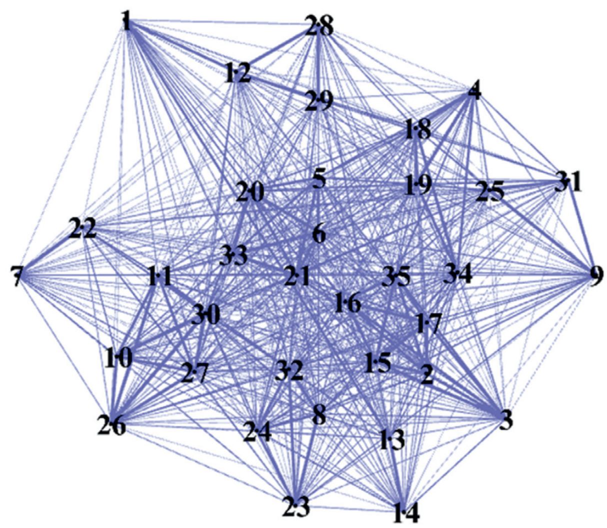


Figure 4: Undirected weighted network model of customer demands.

Table 4: Eigenvalues of the weighted network nodes.

Node	Degree	Weighted degree WD	Weighted aggregation	Aggregation coefficient WC	Weighted network's comprehensive eigenvalues
Cr_1	35	6.3	132.2	7.92	4.05
Cr_2	35	8.9	129.8	3.69	1.97
Cr_3	35	8.1	130.4	4.53	2.38
Cr_4	35	7.4	131.1	5.54	2.87
Cr_5	35	8.0	130.5	4.66	2.44
Cr_6	35	8.5	130.0	4.08	2.16
Cr_7	35	5.5	133.0	10.75	5.45
Cr_8	35	8.2	130.3	4.41	2.18
Cr_9	35	7.0	131.5	6.26	3.23
Cr_{10}	35	7.8	130.7	4.93	2.57
Cr_{11}	35	8.4	130.1	4.19	2.21
Cr_{12}	35	7.3	131.2	5.71	2.96
Cr_{13}	35	6.8	131.7	6.68	3.44
Cr_{14}	35	6.2	132.3	8.21	4.19
Cr_{15}	35	9.9	128.6	2.92	1.60
Cr_{16}	35	9.8	128.7	2.98	1.63
Cr_{17}	35	9.7	128.8	3.05	1.66
Cr_{18}	35	8.1	130.4	4.53	2.38
Cr_{19}	35	8.2	130.3	4.41	2.32
Cr_{20}	35	8.8	129.7	3.78	2.01
Cr_{21}	35	9.6	128.9	3.12	1.69
Cr_{22}	35	6.3	132.2	7.92	4.05
Cr_{23}	35	7.3	131.2	5.71	2.96
Cr_{24}	35	7.9	130.6	4.79	2.51
Cr_{25}	35	7.2	131.3	5.88	3.04
Cr_{26}	35	7.2	131.3	5.88	3.04
Cr_{27}	35	8.7	129.8	3.88	2.06
Cr_{28}	35	6.7	131.8	6.90	3.54
Cr_{29}	35	6.5	132.0	7.38	3.78
Cr_{30}	35	10.2	128.3	2.73	1.51
Cr_{31}	35	6.4	132.1	7.64	3.91
Cr_{32}	35	9.2	129.3	3.43	1.84
Cr_{33}	35	7.1	131.4	6.07	3.13
Cr_{34}	35	8.7	129.8	3.88	2.06
Cr_{35}	35	9.2	129.3	3.43	1.84

Table 5: Initial P value of every customer demand.

p_1	p_2	p_3	p_4	p_5	p_6	p_7	p_8	p_9	p_{10}	p_{11}	p_{12}
0.89	0.17	0.31	0.48	0.33	0.24	1	0.24	0.61	0.38	0.25	0.52
p_{13}	p_{14}	p_{15}	p_{16}	p_{17}	p_{18}	p_{19}	p_{20}	p_{21}	p_{22}	p_{23}	p_{24}
0.68	0.95	0.04	0.05	0.06	0.31	0.29	0.18	0.07	0.9	0.52	0.36
p_{25}	p_{26}	p_{27}	p_{28}	p_{29}	p_{30}	p_{31}	p_{32}	p_{33}	p_{34}	p_{35}	—
0.54	0.54	0.2	0.72	0.80	0	0.85	0.13	0.58	0.2	0.13	—

number of consecutive iterations of the cluster center without a change is set to 50. The value of λ is set to 0.5 in Matlab R2014b. Figure 5 shows the results.

In Figure 5, when $\lambda = 0.5$, after 40 iterations, the fitness value becomes stable at 22.20, indicating that the clustering center no longer changes and the value of λ is reasonable. There are nine clusters, where the dots represent demand items, demands in the same category are connected by straight lines, and different categories are displayed in various colors. According to the coordinate points corresponding to each demand, the customer demands displayed in Table 1 can be grouped into nine categories, {(Cr_1, Cr_{13}, Cr_{14}), (Cr_2, Cr_3, Cr_{15}, Cr_{16}, Cr_{17}, Cr_{35}), (Cr_4, Cr_{18}, Cr_{19}, Cr_{34}), (Cr_5, Cr_6, Cr_{20}, Cr_{21}, Cr_{33}), (Cr_7, Cr_{22}), (Cr_8, Cr_{23}, Cr_{24}, Cr_{32}), (Cr_9, Cr_{25}, Cr_{31}), (Cr_{27}, Cr_{10}, Cr_{11}, Cr_{26}, Cr_{30}), (Cr_{12}, Cr_{28}, Cr_{29})}. The customer demands for the control service system can then be divided into nine different subject categories, as shown in Table 6.

3. Function Domain Determination for a Control Service System

3.1. Overview of QFD. QFD, a typical customer-driven design method, was first proposed by Mizuno and Akao [51]. The basic display tool of QFD is the house of quality, an intuitive matrix framework for the conversion of customer demands [52]. As a customer-driven product development method, it is a simple and logical demand conversion tool. At present, the QFD configuration process can be broken down into four stages: the product planning quality house, the parts' development quality house, the process planning quality house, and the production planning quality house (see Figure 6). These four stages use various expansion tables to transform the important parts of the demands downward, step by step, to ensure that the product design process does not deviation from the customer's requirements.

In QFD, the correlation matrix is used to express the complex relation between every demand item and every technical feature of the product [53]. After determining the correlations between a customer's demands and the product's technical characteristics, the importance of the latter can be further determined. As shown in Table 7, a set of symbols is generally used to indicate the degree of correlation.

Furthermore, the product's technical features can be calculated by the equations

$$\mathrm{TIR}_j = \sum_{i=1}^{n} \mathrm{CIR}_i \times R_{ij}, \ (i = 1, 2, \ldots, n; \ j = 1, 2, \ldots, m),$$
$$\mathrm{TIR}'_j = \frac{\mathrm{TIR}_j}{\sum \mathrm{TIR}_j}, \ (j = 1, 2, \ldots, m), \tag{22}$$

where n represents the number of customer demands, m represents the number of the product's technical features, CIR_i is the weight of the ith customer demand item, R_{ij} is the value of the correlation symbol between the ith customer demand item and the jth product technical feature item, TIR_j is the weight of the jth product technical feature item, and TIR'_j is the relative weight of the jth product technical feature item.

3.2. Function Planning for a Control Service System. After the customer demands have been standardized, a mapping analysis between the demand domain and the function domain is carried out. The system's functional characteristics are the customer's requirements, described in engineering and technical language. The control service system usually takes into consideration the process requirements, performance requirements, working environment, industry standards, and so on, as well as functional characteristics. For example, the equipment must be able to process multiple products. Therefore, the system should be compatible with multiple models. The customer demands include the real-time display of workpiece information. Therefore, system function monitoring is required. The customer demands also involve low labor intensity and the ability to convert quickly between different models of products. Therefore, the system must have the capability of automatically switching models. Table 8 shows the functional characteristics of the system, following the analysis.

In addition, some requirements in the customer demand domain have constraints on other functional features, although they might not individually correspond to specific functional features. For example, economic requirements hold throughout the entire design process because cost factors must be considered for every function. Therefore, a HoQ of system functions should be built to analyze the correlations between customer demands and system functional characteristics and clarify the system design's focus (see Figure 7).

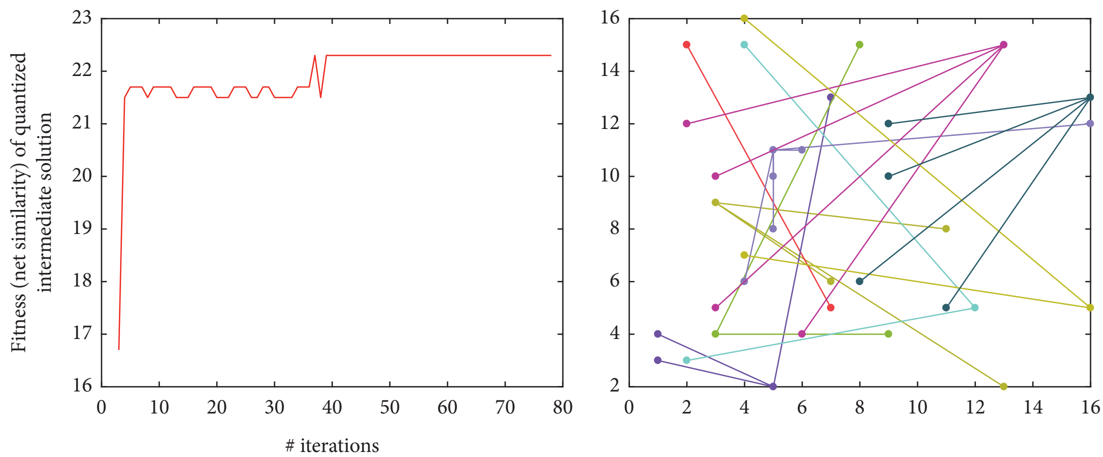


Figure 5: Clustering of customer demands.

Table 6: Architecture of customer demands.

Primary customer demands	Secondary customer demands	Tertiary customer demands
Customer demands for a control service system	Information security, CR_1	Cr_1, Cr_{13}, Cr_{14}
	Operability, CR_2	Cr_2, Cr_3, Cr_{15}, Cr_{16}, Cr_{17}, Cr_{35}
	Alarm prompt, CR_3	Cr_4, Cr_{18}, Cr_{19}, Cr_{34}
	Information query, CR_4	Cr_5, Cr_6, Cr_{20}, Cr_{21}, Cr_{33}
	User-friendly interface, CR_5	Cr_8, Cr_{23}, Cr_{24}, Cr_{32}
	System program, CR_6	Cr_{12}, Cr_{28}, Cr_{29}
	Error-proof design, CR_7	Cr_9, Cr_{25}, Cr_{31}
	Maintainability, CR_8	Cr_1, Cr_{10}, Cr_{11}, Cr_{26}, Cr_{30}
	Economy, CR_9	Cr_7, Cr_{22}

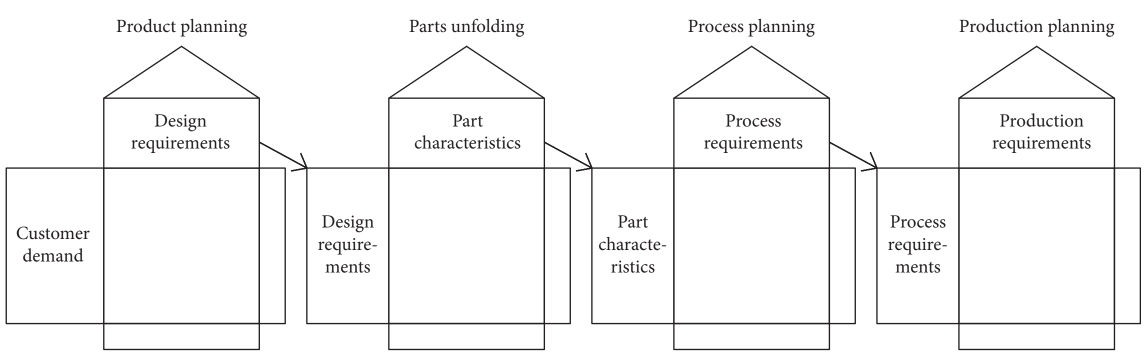


Figure 6: Four stages of QFD configuration.

Table 7: Evaluation and decision table for the correlations between the demand and technical characteristics.

Symbol	Value	Meaning
○	5	Strong correlation between the demand and technical characteristics
□	3	Medium correlation between the demand and technical characteristics
△	1	Weak correlation between the demand and technical characteristics
	0	No correlation with technical characteristics

Following the functional planning output of the HoQ, the designer can clarify major and minor points in the design process, focus on the main points, and avoid deviating from the customer's directions due to personal experience and cognitive limitations. The control service system requires nine functions: FR_1, compatibility with multiple models,

Table 8: Functional characteristics of the control service system.

Name	FR_1	FR_2	FR_3	FR_4	FR_5
Paraphrase	Compatible with multiple models	Automatic switching model	User login	Alarm function	Device driven
Name	FR_6	FR_7	FR_8	FR_9	—
Paraphrase	Automatic feeding	Multiple working modes	Monitoring function	Humanized design	—

Demand	Weights	System features: Compatible with multiple models	Automatic model switching	User login	Alarm function	Device driver	Automatic feeding	Multiple working modes	Monitoring function	Humanized design
Information security	0.0812	△		○					△	□
Operability	0.1882	□	○	□		□	□	○		□
Alarm prompt	0.1637	△			○	□				
Information query	0.0977					△	□		○	□
Pleasant interface	0.0636		□	△				○	□	○
System program	0.0783	○	○			□		□		
Error-proof design	0.0737	□	□		□		□			
Maintainability	0.1922	□			△	○				
Economy	0.0613	△			□	○				
Weights		4.0499	1.7444	1.0342	1.4157	2.6558	1.0788	1.4939	0.7605	1.4193
Relative weights		0.2587	0.1114	0.0661	0.0905	0.1696	0.0689	0.0954	0.0486	0.0907
Target expectations		Meet contract and functional requirements	Meet functional requirements	Meet contract and functional requirements	Meet contract and functional requirements	Meet contract and functional requirements	Meet contract and functional requirements	Meet contract and functional requirements	Meet functional requirements	Meet functional requirements

Figure 7: HoQ of the functional planning for the control service system.

FR_2, automatic model switching, FR_3, a user login, FR_4, an alarm function, FR_5, being device driven, FR_6, automatic feeding, FR_7, multiple working modes, FR_8, a monitoring function, and FR_9, humanized design. The relative importance levels of each functional characteristic are shown in Table 9.

4. Structure Domain Determination for the Control Service System

4.1. Overview of AD. The core of AD is the domain. According to Suh, the domain is the boundary of four design activities with different types and different modes in the product design phase [54]. The domains in axiomatic theory are the customer domain, the function domain, the structure domain, and the process domain. Between two adjacent design domains, the left domain represents the "what," that is, the purpose, and the right domain represents the "how," that is, the method that satisfies the left domain. The hierarchical structure and zigzag mapping are the core methods of the AD design process [55]. As depicted in Figure 8, the hierarchical structure describes the relation of various elements within the domain, and the zigzag mapping represents the mapping of the domains.

Figure 8(a) illustrates the hierarchical structure of collection self-decomposition in the domain. A group of subsystems can be composed of elements in the domain according to certain rules. Here, a top-down method is used to decompose the abstract total function into subfunctions, layer by layer, until the final design is produced. The correlations of the functional, structural, and process domains are described according to the zigzag mapping in Figure 8(b). The zigzag mapping is a top-down approach in the form of a Z, and it repeats the mapping of the same and different levels in every domain until the previous domain can no longer be decomposed.

To judge the reasonability of the design process, AD theory proposes a design axiom. While mapping the function domain to the structure domain, the designer can judge the appropriateness of the mapping according to the design axioms. The entire mapping can be described as

$$\{FR\}_{m\times 1} = A_{m\times n}\{DP\}_{n\times 1}, \tag{23}$$

where $\{FR\}_{m\times 1}$ represents the FRs, $\{DP\}_{n\times 1}$ represents the DPs, and $A_{m\times n}$ represents the design matrix, which can be expressed as

Table 9: Relative importance of system functional characteristics.

Features	FR_1	FR_2	FR_3	FR_4	FR_5	FR_6	FR_7	FR_8	FR_9
Relative weight	μ_1 0.2587	μ_2 0.1114	μ_3 0.0661	μ_4 0.0905	μ_5 0.0169	μ_6 0.0689	μ_7 0.0954	μ_8 0.0486	μ_9 0.0907

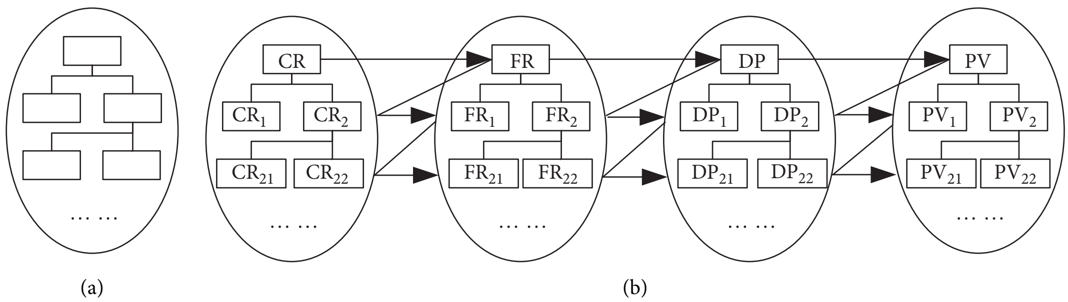


Figure 8: (a) Hierarchy and (b) zigzag mapping of AD.

$$A_{m\times n} = \begin{bmatrix} A_{11} & A_{12} & \cdots & A_{1n} \\ A_{21} & A_{22} & \cdots & A_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ A_{m1} & A_{m2} & \cdots & A_{mn} \end{bmatrix}, \quad (24)$$

where the matrix elements are determined by $A_{ij} = (\partial FR_i)/(\partial DP_j)$ $(i = 1, 2, \ldots, m;\ j = 1, 2, \ldots, n)$.

In an actual design, the numbers of FRs and DPs will not be the same. As shown in Table 10, given the relation between the numbers of FRs and the number of DPs, the design can be split into an ideal design, a redundant design, and a coupling design.

4.2. House of Quality for Risk Prediction. Once the basic structure of a control service system is described, high-risk modules in the structure domain can be predicted and analyzed to determine potential failure modes and analyze the possible consequences. These measures can be taken in advance. Because the importance of the elements in the domain cannot be evaluated in AD, this paper introduces a risk prediction HoQ model. This model transmits the decomposition and mapping results of the AD functional and structural domains to the HoQ, builds a risk prediction HoQ, and proposes the ERPN to measure every structural module and clarify the key points of the process.

The concept of ERPN is based on risk probability number. Taking into account the importance of the system functions, the system structure can be optimized to determine measures to reduce the chance of potential failure. The formula for the ERPN is

$$\mathrm{ERPN} = \mu_j \cdot I_k \cdot S \cdot O \cdot D, \quad (25)$$

where μ_j is the relative weight of the jth system function characteristic in the HoQ, I_k is the weight of the kth subfunction characteristic in the risk prediction HoQ, and S is the severity (see Table 11).

Table 12 shows the scoring criteria for the frequency O.

Table 13 shows the scoring criteria for the degree of detection D.

4.3. Structure Domain Solution of the Control Service System. The system's functional characteristics are only a visual description of the control system and do not correspond directly to the basic composition of the system. Therefore, a practical system design is impossible. According to the principle of functional decomposition mapping in AD, the basic structure of the water heater liner top press control system can be determined through the zigzag mapping. Functions can then be transformed from the conceptual to the specific, and an overall system structure can be built. Finally, when all the basic components of the system are worked out, the structure can be optimized by establishing a HoQ for risk prediction.

In the example of the decomposition map of the automatic switching model function, FR_2, the corresponding basic structure module and risk prediction of the basic structure in question are proposed. The water heater tank capping press has an inner liner press and an inner liner top cover automatic feeding device. The automatic model switching function, FR_2, requires that the automatic feeding device of the top cover recognize different workpiece types and automatically feed different types of top covers. According to the equipment's execution sequence, FR_2 can be decomposed into two subfunctions, such as sending the workpiece model, FR_{21}, and receiving the workpiece model, FR_{22}. The corresponding mapping structures are the model identification module of the PLC system, DP_{21}, and the model identification module of the ABB robot control system, DP_{22}. The design equation of the mapping is thus

$$\begin{bmatrix} FR_{21} \\ FR_{22} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} DP_{21} \\ DP_{22} \end{bmatrix}. \quad (26)$$

The subfunctions of the sent workpiece model, FR_{21}, can be decomposed into the model selection carrier, FR_{211}, and the workpiece model selection item, FR_{212}, recognizes the selected workpiece model of the PLC system, FR_{213}, and transmits the

Table 10: Ideal, redundant, and coupling designs.

Design name	Condition	Design matrix
Ideal design	Number of FRs = number of DPs	Diagonal matrix
Redundant design	Number of FRs < number of DPs	Triangular matrix
Coupling design	Number of FRs > number of DPs	Nontriangular matrix and nondiagonal matrix

Table 11: Severity (S) scoring criteria.

Harm	Assessment criteria: severity of the impact on the system	Severity level
No warning hazard	No alarm is issued when the equipment is faulty and the control system is completely out of order	10
Warning hazard	Alarm when the equipment is faulty and the control system fails	9
Very serious	Has a serious impact on the control system and the system is difficult to repair	8
Serious	Has a serious impact on the control system, but the system can be partially repaired	7
Medium	Has a certain impact on the control system, but the system can be repaired	6
Low	Has a certain impact on the control system, but the system can be repaired completely	5
Very low	Has less impact on the control system and the system can be repaired more quickly	4
Slight	The impact on the control system is small, and the system can be repaired quickly	3
Very	The impact on the control system is very slight, and the system can be easily repaired	2
Nothing	No impact on the control system, and the system can work normally	1

Table 12: Frequency (O) scoring criteria.

Possibility of failure	Evaluation criteria: frequency of occurrence	Frequency
Very high	Greater than 1/2	10
	About 1/3	9
High	About 1/8	8
	About 1/20	7
Moderate	About 1/80	6
	About 1/400	5
	About 1/2000	4
Low	About 1/15,000	3
	About 1/150,000	2
Very low	Less than 1/150,000	1

Table 13: Scoring criteria for the degree of detection D.

Detectability level	Evaluation criteria: the possibility of detecting the cause of system failures in the prior art	Level
Infinitesimal	The prior art cannot detect the cause of the failure of the control system	10
Very tiny	Existing technology has difficulty detecting the cause of the failure of the control system	9
Tiny	Existing technology has more difficult detecting the cause of the failure of the control system	8
Very low	Need a control system designer to investigate the cause of the fault	7
Low	A technician can discover the cause of the failure	6
Medium	The control system has alarm tips, but does not display fault information	5
Higher	The control system has alarm tips and displays fault information	4
High	The cause of the fault can be determined by a simple test instrument	3
Very high	The cause of the failure can be visually identified	2
Almost certainly	The cause of the fault can be detected almost certainly	1

workpiece model information, FR_{214}. The working principle involves receiving the input signal of the workpiece model, generating a control signal after the program is run, and then issuing a control command. The corresponding mapping structures are the selection screen, DP_{211}, the workpiece selection list, DP_{212}, the PLC model judgment program, DP_{213}, and PLC workpiece model information output point, DP_{214}. The design equation of the mapping is

$$\begin{bmatrix} FR_{211} \\ FR_{212} \\ FR_{213} \\ FR_{214} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} DP_{211} \\ DP_{212} \\ DP_{213} \\ DP_{214} \end{bmatrix}. \tag{27}$$

The subfunctions of the received workpiece model, FR_{22}, can be decomposed into the ABB robot input workpiece

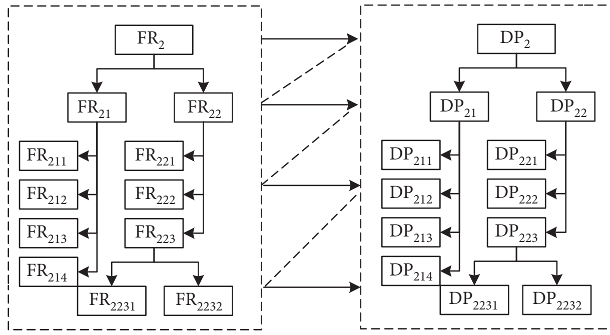


Figure 9: The zigzag mapping of FR_2.

		Importance	Layer 1	Layer 2		Layer 3						
			DP_2	DP_{21}	DP_{22}	DP_{211}	DP_{212}	DP_{213}	DP_{214}	DP_{221}	DP_{222}	DP_{223}
Layer 1	FR_2	μ_2										
Layer 2	FR_{21}	4		1	0							
	FR_{22}	4		1	1							
Layer 3	FR_{211}	3				1	0	0	0			
	FR_{212}	2				0	1	0	0			
	FR_{213}	3				0	0	1	0			
	FR_{214}	3				0	0	1	1			
	FR_{221}	2								1	0	0
	FR_{222}	3								1	1	0
	FR_{223}	4								0	0	1
Importance				8	4	2	3	6	3	5	3	4
ERPN				64.17	32.08	3.56	5.35	13.37	10.03	13.37	8.03	24.06

Figure 10: The risk prediction house of quality of DP_2.

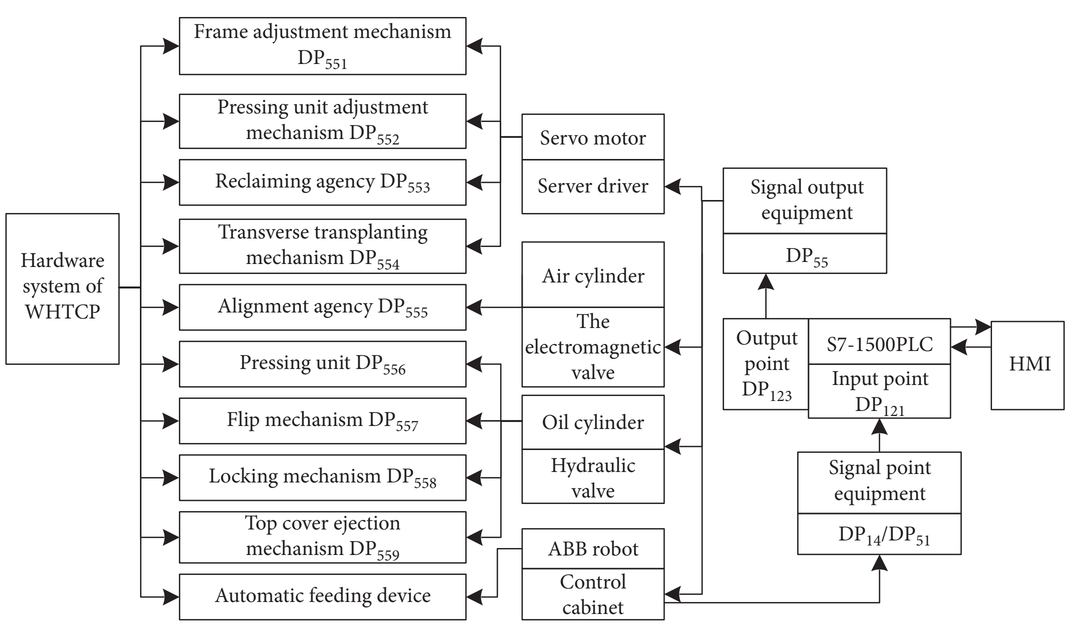


Figure 11: Hardware structure of the control service system.

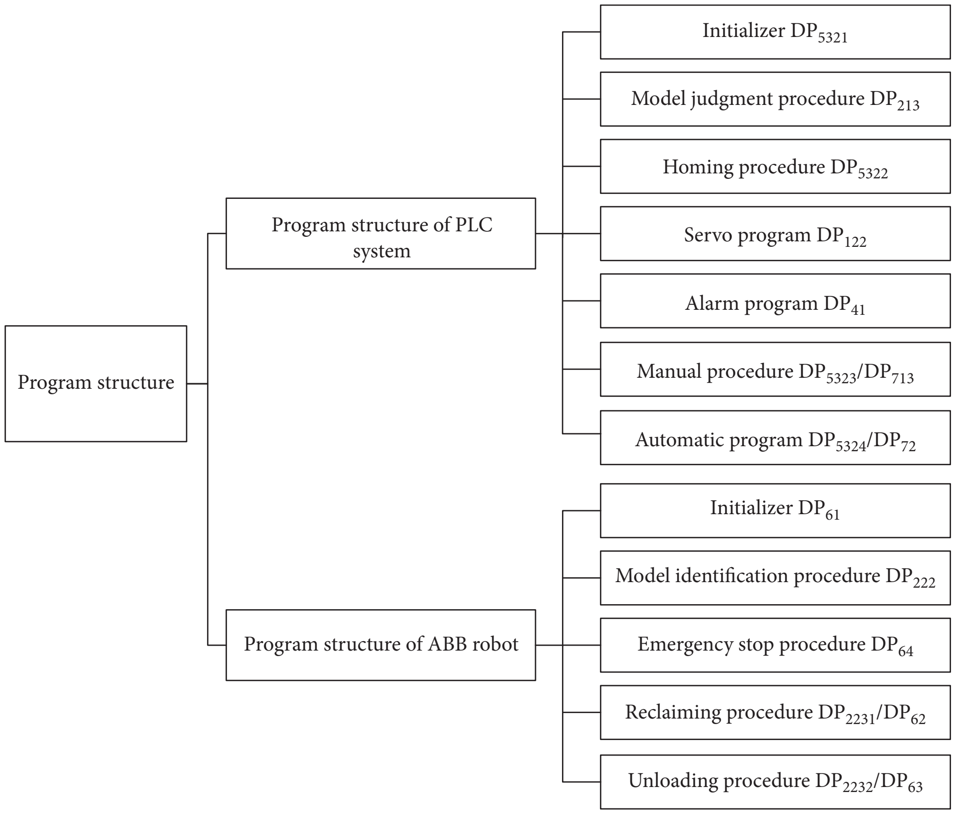


Figure 12: Control service system's program structure scheme.

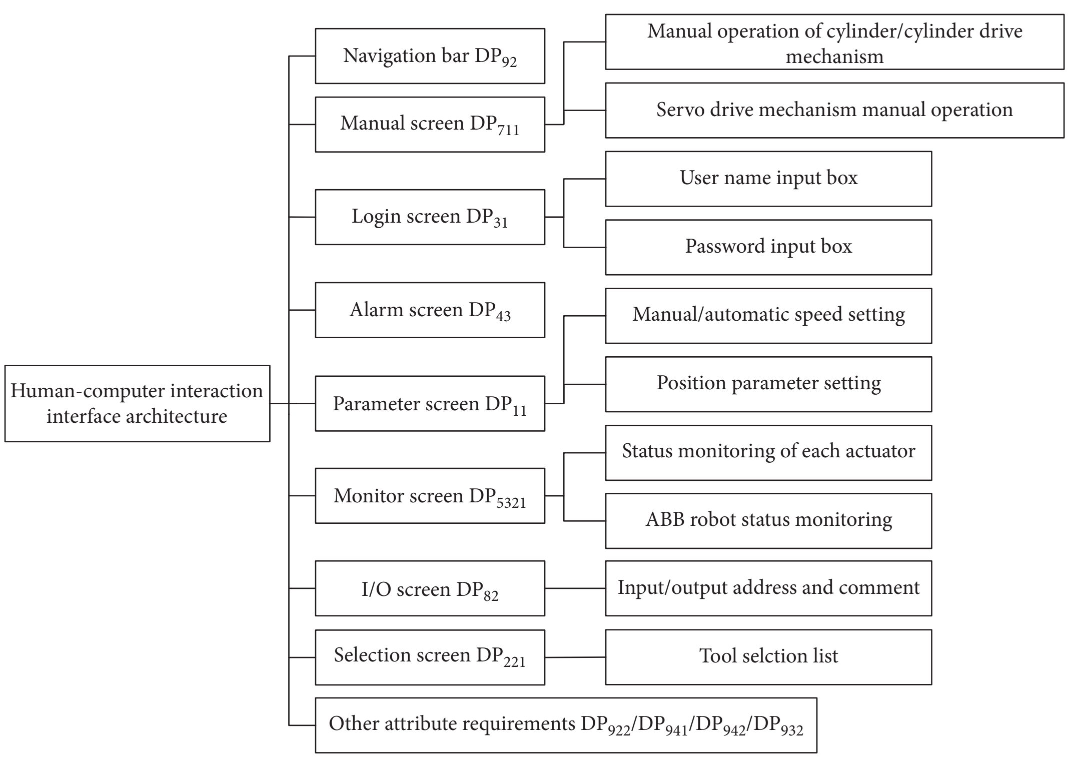


Figure 13: The human-machine interface of the control service system.

Table 14: Analysis of the potential failure risk of the control service system.

System	Module	Structure	Risk order	Fault description	Measures
Hardware	Solenoid valve	DP_{55}	97.69	Solenoid valve does not work when energized	Select an excellent solenoid valve, with timely detection and replacement
	Signal input device	DP_{14} DP_{51}	93.13 81.41	Unstable signal detection	Choose appropriate signal detection components and avoid vibration
	Servo motor	DP_{551} DP_{552} DP_{553} DP_{554} DP_{13}	67.84 67.84 67.84 67.84 66.23	Servo drive alarm	The installation and cable routing of the servo drive adhere to strict anti-interference measures; the servo drive is separately equipped with a 24 V DC power supply to ensure the stability of the current in the servo system
	Signal input element	DP_{52} DP_{121}	61.06 54.33	An abnormal or unstable input signal	Select a distributed PLC, paying attention to whether the power supply voltage of the I/O terminal is normal
	Signal output element	DP_{54} DP_{123}	56.98 37.25	An abnormal or unstable output signal	Select a ground wire of sufficient diameter and add an equipotential shielding plate
Program	Automatic program	DP_{5324}	32.56	Production cycle length	Become familiar with the process flow and plan the system action flow.
	Manual program	DP_{5323}	30.53	Misoperation or wrong action	Set delayed action and add error-proof design
	Alarm program	DP_{41}	26.87	Alarm is not timely	Create different alarm outputs for the different fault types
	Reclaiming program	DP_{62}	24.80	Poor movement	Refine the action; the span between each action command is easily insufficiently large, so set the appropriate speed and turning radius
	Unloading program	DP_{53}	24.80	Incorrect feeding position	Set a low speed when discharging, produce a linear motion, and prevent shaking
HMI	Action command	DP_{931}	13.06	Incorrect operation	Set button delay action and error proof the design
	Operation feedback	DP_{93}	9.79	Operation result unknown	Add operation process indicator and position indicator
	Navigation bar	DP_{92}	8.17	Cannot quickly switch between interfaces	Set a reasonable interface display area
	Element layout	DP_{942}	6.53	Cannot quickly find the operation button	Reasonably arrange the buttons and add notes

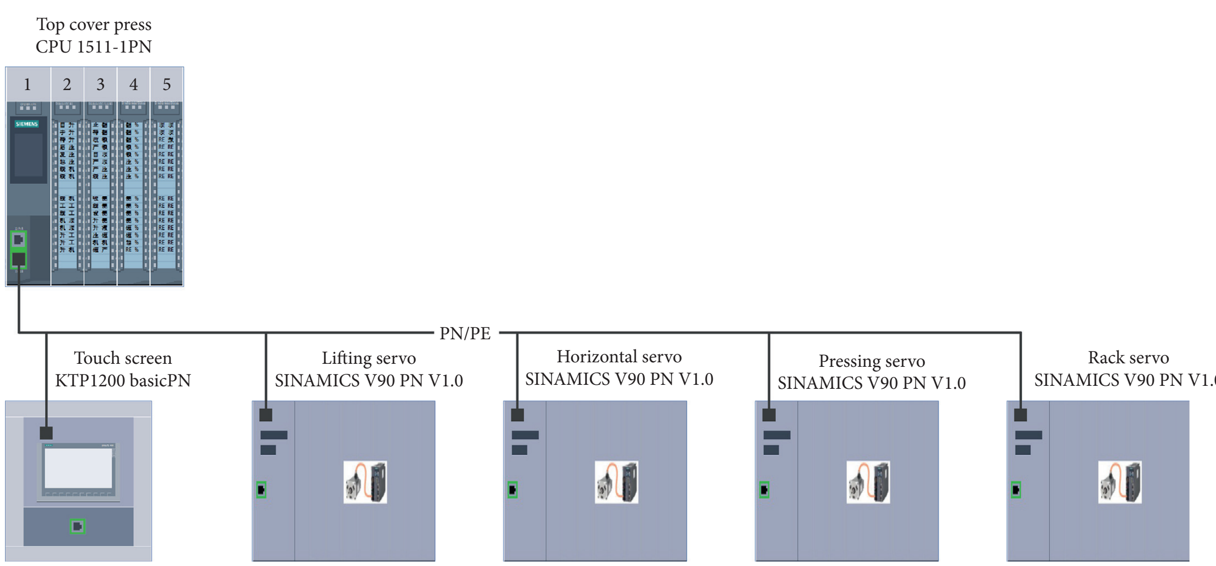


Figure 14: The equipment configuration network diagram of the control system of the water heater tank capping press.

information, FR_{221}, whereas the ABB robot can judge the workpiece model, FR_{222}, and executes the loading action, FR_{223}. The working principle of model, FR_{22}, is to receive input signals, generate control signals after the program is run, and then issue control commands. The function sequence relations are $FR_{221} > FR_{222} > FR_{223}$. The mapping

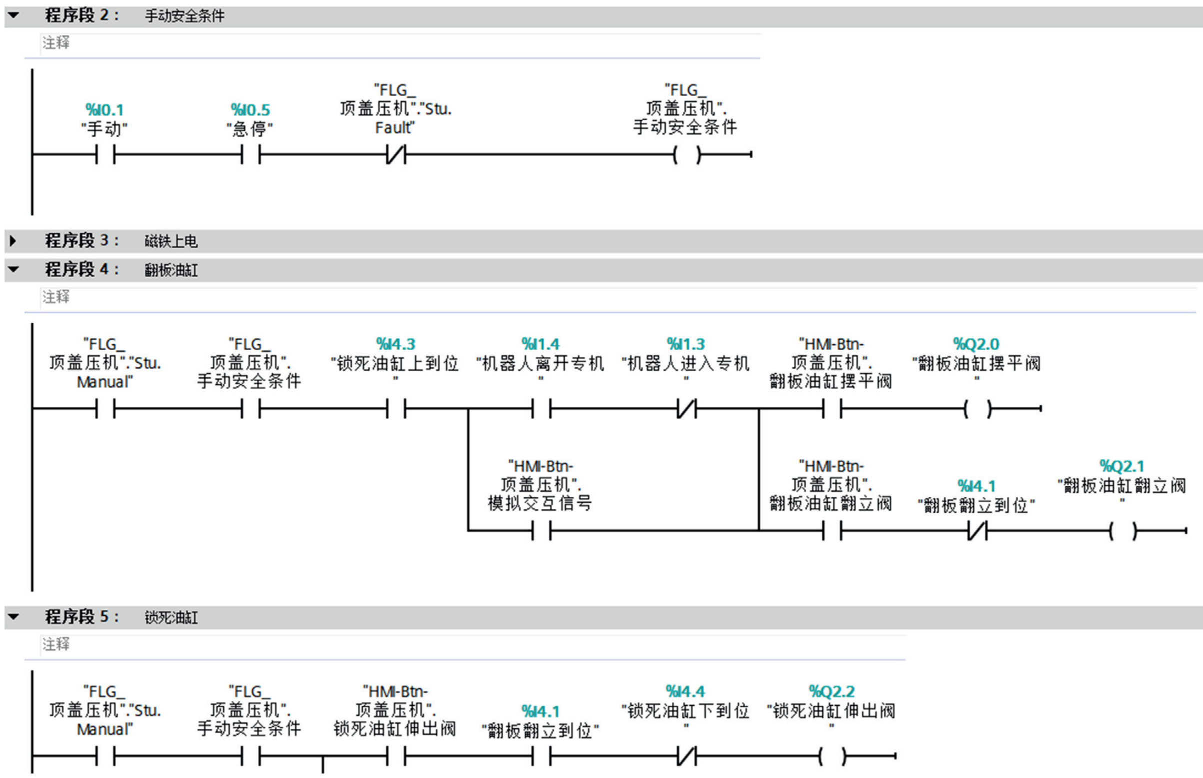


FIGURE 15: Part of the manual program of the water heater tank top press system.

structure is the ABB robot signal input point, DP_{221}, the ABB robot model program, DP_{222}, and feeding control program, DP_{223}. The design equation of the mapping is then

$$\begin{bmatrix} FR_{221} \\ FR_{222} \\ FR_{223} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} DP_{221} \\ DP_{222} \\ DP_{223} \end{bmatrix}. \tag{28}$$

The zigzag mapping of the functional structure of FR_2 is presented in Figure 9.

To reasonably evaluate the importance of each basic structure of DP_2 and clarify the design focus of the system, the risk prediction HoQ can be illustrated according to the decomposed mapping and the zigzag mapping matrix of FR_2. Furthermore, the ERPN of DP_2 can be obtained, as shown in Figure 10.

As shown in Figure 10, the modules of DP_{21}, DP_{223}, and DP_{22} have higher risk sequence numbers. Thus, the designers should focus on analyzing possible failures and incorporate preventive measures during the design process. Similarly, other system functions, such as FR_1 and FR_3 to FR_9 can be decomposed via mapping and solved to obtain all the basic structural modules.

5. Construction of the Control Service System

According to the solution for the functional structure of the control service system, the resulting basic structure can be split into a hardware system, a system program, and a human-computer interaction interface. According to the results of the risk prediction house of quality for each structural module, the structural modules are found to have a higher risk order in the hardware system, system program, or human-computer interaction interface, respectively. During the design stage, designers adopt targeted measures to resolve these potential risks and to reduce their impact on later system debugging. Figure 11 shows the hardware structural scheme of the control service system for the water tank liner top cover press system. Figure 12 shows the system's program structural scheme.

The basic structural schemes related to the human-computer interaction interface are screened to determine those related to the human-machine interaction interface. The basic structural schemes of the human-computer interaction interface should then be combined according to the designer's knowledge of industrial human-computer interaction interfaces. Figure 13 shows the structural design of the human-computer interaction interface of the control service system.

After the hardware system's structure scheme, the system's program structure scheme, and the control service system's human-computer interaction interface structure scheme are combined, the structural modules with higher risk order numbers in every scheme must be determined (see Table 14). An analysis of these modules can determine potential failure modes and the possible consequences, and, on that basis, provide corresponding preventive measures. Potential risks can thus be resolved during the design stage.

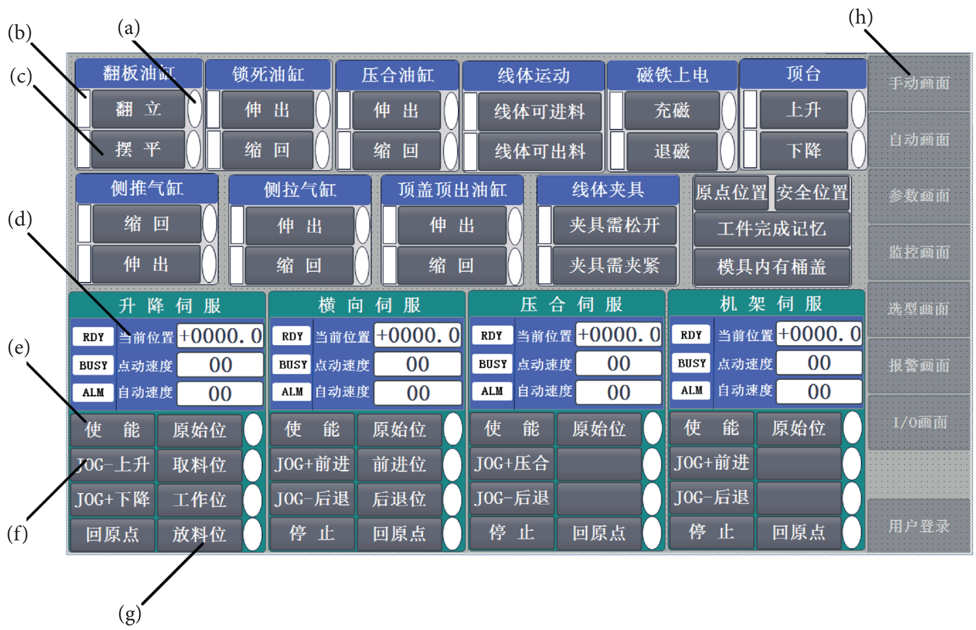
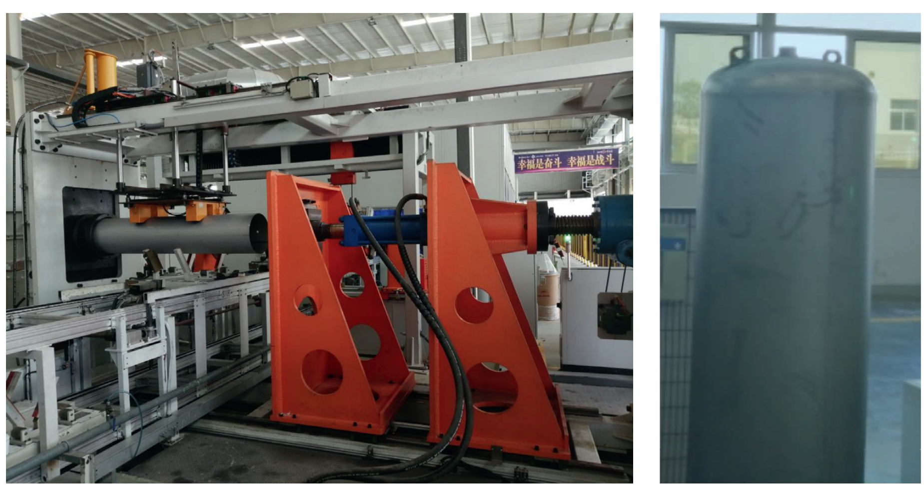


FIGURE 16: Manual operation interface of water heater tank top press system. (a) Operation feedback indication. (b) In-place instructions. (c) Operation button. (d) Servo motor monitoring. (e) Servo motor power up. (f) Servo motor inching control. (g) Step operation. (h) Navigation bar.



(a) (b)

FIGURE 17: The water heater tank capping press.

6. Conclusion

According to the structure scheme of the control system of the water heater tank capping press, the detailed design of each structural module is carried out. In TIAPortal, the CPU1511 of S7-1500, HMI panel, and 4 servo drives form a configuration network, and Profinet industrial Ethernet is used to communicate among each part, as shown in Figure 14.

Then, according to the program structure scheme, the PLC program of the control system of the water heater tank capping press is divided into automatic program module, initialization program module, manual program module, return to the origin program module, alarm program module, and servo motor program module. Part of the manual program module is shown in Figure 15. The touch screen interface design of the control system mainly includes parameter interface, monitoring screen, selection screen, alarm screen, automatic screen, manual screen, and I/O port screen. The manual screen is shown in Figure 16. The main body of the water heater tank capping press is shown in Figure 17.

After the design of the control system is completed, the water heater tank capping press is produced and operated in the actual working environment. The water heater tank capping press works stably and satisfies the production demands well. It is verified that the upper design method can effectively guide the design process of the control system.

The design method preferred in this paper is based on the analysis of customer demands to ensure the accurate input of the demand domain and to complete the mapping between the demand domain and the function domain and between the function domain and the structure domain. This approach makes up for the lack of a single design method, to a certain extent. It also has the advantages of accuracy, clarity, and being a complete system. It can guide the designers to make better design decisions and evaluations during the design process more quickly and improve the design efficiency and quality of the control project. This method improves the cluster analysis of customer demands and proposes a weighted network AP clustering algorithm to determine the characteristics of customers' demands, compensating for the lack of regularization of customers' requirements in traditional QFD and AD designs. On the contrary, the method takes full advantage of QFD and AD design methods, combining the empirical design and AD, not only benefiting from the designer's experience but also avoiding subjective influence. Finally, the effectiveness and feasibility of the proposed method are demonstrated by using the example of the design and production of the control service system for a water heater liner top cover press.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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