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A Comprehensive Decision-Making Approach for Strategic Product Module Planning in Mass Customization

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Abstract: This paper explores the integrated optimization of complex coupled industrial manufacturing systems and production strategies based on user customization needs. Two optimization metrics are considered: one is whether the production process of engineering manufacturing is simplified, and the other is whether it is based on the customization requirements of the customer. These two metrics are interrelated, and cases may even be conflicting. Considering the interdependence between engineering manufacturing and user requirements, this paper develops an integrated customized modular engineering manufacturing process to minimize production and maintenance costs and improve efficiency while meeting user customization requirements. This paper takes expert evaluation as an important decision indicator and optimizes the production process strategy on this basis. Finally, a case study is given to illustrate the applicability of the proposed process model.

Keywords: mass customization; modular design; quality function deployment (QFD); design structure matrix (DSM); decision making

MSC: 90B50

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1. Introduction

In today's fiercely competitive market, customers are increasingly seeking differentiated and innovative products, necessitating manufacturers to offer diversified products and continuously explore innovative methods and adaptive strategies to keep pace with shifting market dynamics [1–3]. Mass customization offers flexibility and personalization across a wide range of products, enabling companies to attain greater variety, large quantities, low costs, and swift delivery [4]. Industries such as automotive, apparel, computers, food, electronics, and even home construction have begun adopting mass customization [5]. Mass customization has emerged as a critical area of focus in production research.

Modularization is a leading practice for achieving mass customization [6]. The strategic planning of product modules enhances product variability by deconstructing product architecture into physically independent units [7]. These units can be extensively customized by replacing, adding, or removing modules [8], thereby simplifying product development, manufacturing, and upgrade processes and facilitating the connection between product life cycle strategy and design [9]. Moreover, modular design methods play a central role in product life cycle and sustainability research. Rapid changes in market trends and customer needs significantly shorten the life cycle of new products [10,11]. However, the flexibility of modular structures establishes a crucial link between product life cycle strategy and design [12], thereby influencing product sustainability [13–15]. Compared to traditional product architecture, the advantages of modular architecture are evident in all stages of the product life cycle [12,16]. The strategic planning of product modules simplifies product development, manufacturing, and upgrade processes. Additionally, it enhances product diversity through reconfiguration (upgrades, modifications, and disassemblies), reduces production time and costs through standardization, promotes economies of scale, and effectively mitigates the product's environmental impact during use and after disposal [9,11,16–21]. A large body of research emphasizes the key role of modularization in mass customization. Evidence demonstrates that modularization effectively meets customer needs for diversity in basic product design and rapid customized delivery [22,23]. Its applications span various industries, including electronics, computers, construction, and automobiles [6–8,24–28]. In the field of engineering, particularly in industrial design, modular design serves as an essential technology for meeting customer demands for diversification and rapid customized delivery in basic product design [29,30].

However, current research highlights that compatibility issues among diverse engineering attributes in complex product module planning can significantly influence strategic, tactical, and operational decisions across the engineering design and production phases [31]. Owing to the inherent uncertainty in new product development, altering product modules will modify specific performance parameters, directly influencing customer purchasing decisions [32]. Consequently, manufacturers must not only meet customer requirements but also address environmental concerns and resource efficiency in the manufacturing process to ensure sustainable production operations [33]. Companies must endeavor to maximize their product offerings by optimizing variety and customization. Simultaneously, they must consider the compatibility of product engineering performance and the impact of product structure relationships during the design process to effectively optimize these coupling tasks. In conclusion, determining innovative work procedures or methods that incorporate the optimal design parameters and module configurations while capturing customer feedback poses one of the key but challenging issues confronting modern enterprises [33,34].

User-requirement-oriented module partitioning requires special attention to user requirement acquisition, requirement-to-function transformation, and module clustering algorithms [35]. Various product design methods have been employed across multiple domains, including reverse engineering, value engineering, the Taguchi method, and quality function deployment (QFD). While the first three approaches emphasize product functionality, they pay less attention to customer requirements and production operations [36]. In contrast, QFD is a customer-centric design method that translates customer requirements into practical functions through multiple stages of product planning, design, and manufacturing, ultimately achieving higher customer satisfaction [37,38]. Numerous studies have proposed the application of QFD to develop a sustainable modular design, which involves transforming technical and component functions from environmental, social, and economic perspectives and evaluating the degree of change in the product life cycle [5,39,40].

Furthermore, due to the inherent uncertainty in new product development, companies also endeavor to maximize their product offerings by optimizing variety and customization. Product development projects encompass numerous coupled activities [41]. Complex coupling activities are involved in fulfilling customer requirements concerning engineering and component characteristics. The Design Structure Matrix (DSM), a common modular approach for planning and launching products [42], has garnered increasing attention for addressing optimization problems in product development projects. A study applied the DSM to products to determine the transmission of activity information and component dependencies between parts, thereby directly and simply evaluating the changes in the sequence of activities, minimizing frequent internal interactions, and reducing component complexity [39,43]. The quantified DSM facilitates overall and local detailed planning from a system perspective, capable of simultaneously generating solutions for different variant designs in a series of products required by various industries [44]. It primarily simplifies the module priority and evaluation module through the Boolean matrix of the complex information within the system, followed by a weighted evaluation of the dependency relationship to define the standard, interface, and diversity of the variation degree of the components. Wagner et al. [45] created and evaluated design concepts by integrating axiomatic design, QFD, and the DSM. Tilstra et al. [46] developed a high-definition design structure matrix (HDDSM) to analyze product component relationships and evaluate product structural features. Ali et al. [47] used the DSM and axiomatic design theory to modularize the system structure. It can be seen that the DSM is an important analytical tool for system modeling and design, especially for design decomposition and integration.

Inspired by these studies, this research endeavors to provide a comprehensive and cohesive method for product module planning and decision making, with a primary focus on satisfying user needs and optimizing functional module configuration. To achieve this goal, a two-stage decision-making model is proposed, integrating customer requirements, product structure, engineering and component characteristics, competitive analysis, and the optimization of design tasks through the incorporation of QFD and DSM methods in a sequential manner. Phase 1 addresses product variable conditions, converts customer conditions into product specifications, and systematically delineates product specifications. Phase 2 focuses on product component composition and configuration to meet specification requirements. This approach enables the customization of products to meet the specific needs and preferences of customers, while also considering the compatibility of product engineering performance and the relationships within the product structure during the design process.

The remainder of this article is summarized below. Section 2 summarizes the materials and methods used in this study. Then, Section 3 presents the analysis of the case study results. This paper is discussed in Section 4, the research limitations and future developments are discussed in Section 5, and conclusions are finally given in Section 6, providing managerial insights and research contributions.

2. Materials and Methods

2.1. Research Flowchat

The case study method is a proper research method based on an in-depth investigation of a specific topic. This work is based on this research method and integrates DSM and MFD methods into the modularization process of the injection molding machine (IMM). As shown in Figure 1, the research framework is divided into two phases. The first phase is system integration engineering, which focuses on translating customer conditions into product specifications and further implementing systematic product specification segmentation. This phase is divided into three steps: transforming customer requirements into engineering characteristics, planning product subsystems, and forming a subsystem modular structure. In the modularization process, customer requirements are used as information inputs, which are obtained through frequent interactions between designers and customers. In this process, customer requirements are translated into engineering features and then different component features are provided to achieve customer satisfaction. The second phase is component integration engineering, which aims to configure product components to fulfil system requirements. This phase is divided into three steps: transforming engineering characteristics into component characteristics, planning product components, and forming the structure of component modules. Ultimately, this approach results in product module configurations that satisfy customer conditions and reduce product variability.

2.2. Phase 1: System Integration Engineering

First, the House of Quality (HOQ) needs to acquire the customer's requirements (CRs). The CRs for modularization primarily stem from the market demand for product specifications. The Analytic Hierarchy Process (AHP) is a theory of measurement through pairwise comparisons and relies on the judgements of experts to derive priority scales [48]. It is utilized to obtain the weights of CRs. Evaluations are scored using a nine-point scale, with higher numbers indicating greater importance. The CRs (set as m items) are filled into the row (i) and column (j) of the judgment matrix, and the importance of satisfying customers is compared in pairs. $C = [c_{ij}]_{m \times m}$ represents the customer satisfaction, and the overall matrix is as follows:

$$C = \begin{bmatrix} 1 & 3 & 5 & 7 & 9 \\ 1/3 & 1 & 3 & 5 & 7 \\ 1/5 & 1/3 & 1 & 3 & 5 \\ 1/7 & 1/5 & 1/3 & 1 & 3 \\ 1/9 & 1/7 & 1/5 & 1/3 & 1 \end{bmatrix} \tag{1}$$

where C_{ij} represents the importance of requirement i relative to j in satisfying customers. The lower triangle area on the left is the reciprocal of the upper triangle area on the right side of the matrix, that is, $c_{ij} = 1/c_{ij}$.

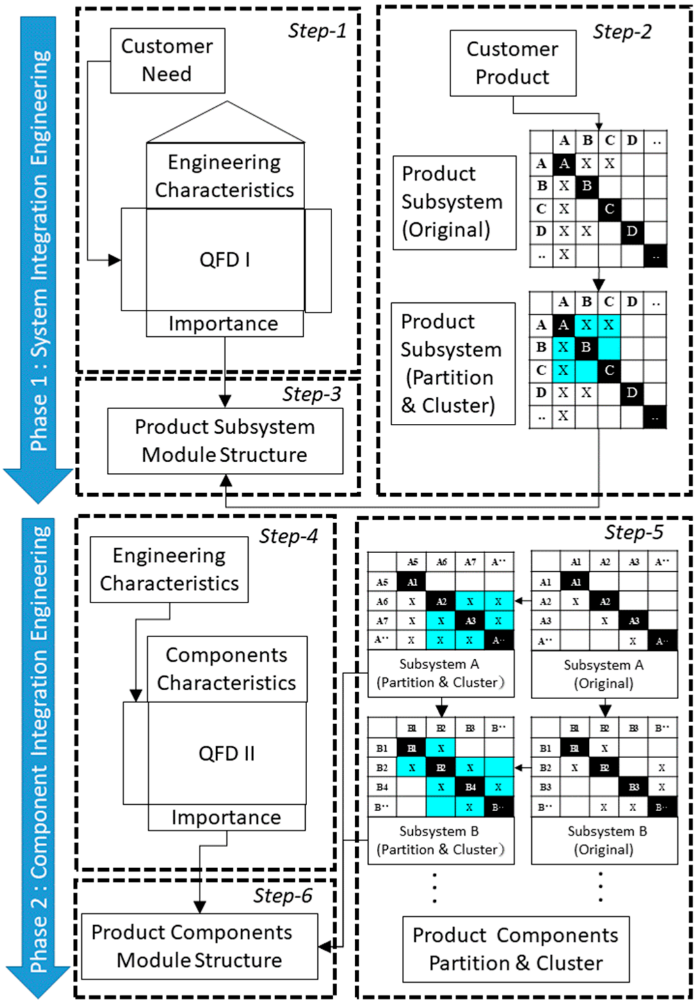


Figure 1. Research framework for modular design method.

The judgment matrix is established to obtain the weight of CRs, denoted as W_i, and its equation is as follows:

$$W_i = \left[\prod_{j=1}^{m} c_{ij}\right]^{1/m} / \sum_{i=1}^{m}\left[\prod_{j=1}^{m} c_{ij}\right] \tag{2}$$

where $i = 1, 2 \cdots m$, and $j = 1, 2 \cdots m$.

According to the CR importance W_i $(i = 1, 2, \cdots, m)$ analyzed by the AHP, the left side of QFD I is filled in. Then, experts discuss and define engineering characteristics (ECs), giving a correlation importance score $h_k (k = 1, 2, \cdots n)$ between CRs and ECs. If an EC is related to multiple CRs, and W_i is high, h_k will be high, which indicates that this EC is extremely important to the product. The equation of h_k is as follows:

$$h_k = \sum_{i=1}^{m} w_i r_{ik} \tag{3}$$

If items $k1$ and $k2$ of EC are contradictory, when $h_{k1} > h_{k2}$, $k1$ should be improved. According to the competition assessments, if $k1$ is higher than the current market level, $k2$ is not qualified. Then, it should be evaluated whether $k1$ can be reduced, and $k2$ improved. The specific module configuration can be selected by customers. In this study, h_k refers to the degree of influence of the subsystem on the product. It initially defines the purpose of the module development.

Competitor assessment $M_i(i = 1, 2, \cdots, m)$ is the data returned by customer evaluation. The evaluation uses a five-point scale, where 1 means unqualified, 3 means moderate, and 5 means excellent. Based on the competitive assessment and the engineering conflict of HOQ, experts can decide whether to promote or maintain ECs. In this way, the construction of QFD I can be formed.

Considering the product as a system, the subsystems are decomposed according to their functions. The ECs are mapped into the DSM matrix. When the number of row and column subsystems in the DSM model of product P is subsystem s (Subsystem A, Subsystem B, . . . Subsystem S), they are encoded into the matrix according to the order from left to right and top to bottom. The matrix activity is shown in Figure 2.

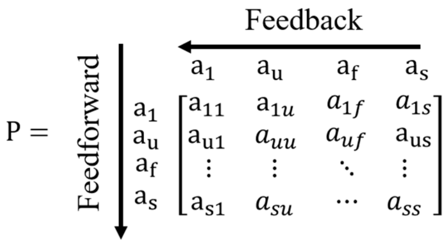


Figure 2. Internal activities of the DSM.

According to Figure 3, the relationship between the elements in the matrix can be determined, and the DSM subsystem clustering can be performed [49]. The three relationships are parallel relationships (independent), sequential relationships (dependent), and coupled relationships (interdependent), which are described in detail as follows:

- Parallel relationship: The two tasks have no information exchange and exist as independent functions. Its characteristic is that tasks A and B can run simultaneously.
- Sequential relationship: The relationship between two tasks is that they exchange information unidirectionally. Its characteristic is that tasks A and B occur one after another.
- Coupled relationship: Two tasks easily exchange information with each other, meaning tasks A and B interact bidirectionally. Task A requires input from Task B and vice versa. Tasks A and B usually need to exchange information multiple times to complete their function.

The purpose of the division is to rearrange the sequence of DSM matrix elements. This process changes the information to the triangular area below the diagonal as much as possible to form parallel relationships and sequential relationships, thereby reducing the information of coupling relationships in the matrix. The process of swapping and sorting the element positions of the DSM model subsystem is expressed as $Q(u \to f)$, and the specific process is as follows:

Swap row elements of $Q(u \to f)$: $(a_{1u}\ a_{2u} \ldots\ a_{su})^T = \left(a_{1f}\ a_{2f} \ldots\ a_{sf}\right)^T$

Elemental swap of $Q(u \to f)$: $(a_{u1}\ a_{u2} \ldots\ a_{us}) = \left(a_{f1}\ a_{f2} \ldots\ a_{fs}\right)$

The purpose of clustering is to classify elements with close relationships in the matrix into the same block so that the relationship between the elements in the block is high, and the relationship between the block and other parts is minimal. In confirming the priority order, the subsystem with the highest ranking in the matrix should be the standard specification element to minimize the impact on subsequent systems.

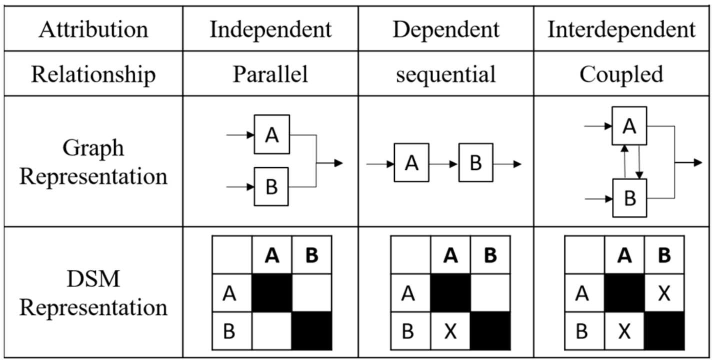


Figure 3. Three types of element relationships.

2.3. Phase 2: Component Integretion Engineering

Then, the importance of ECs and the system architecture of QFD I is integrated to define subsystem standard modules or specification replacement modules. Subsystems with higher importance are more likely to have component modules with higher variability. The importance of a subsystem can be defined as the degree of product variation due to CRs. When the degree of variation in higher-priority subsystems is too high, it may affect the product's customization level.

Subsystem s is divided into DSM clustering, and matrix activities are performed according to Equation (4):

$$
\begin{gathered}
a_1 = \begin{matrix} \\ (a_s)_1 \\ (a_s)_2 \\ \vdots \\ (a_s)_z \end{matrix}
\begin{matrix} (a_s)_1 & (a_s)_2 & \cdots & (a_s)_z \\ \left[\begin{matrix} (a_1)_{11} \\ (a_1)_{21} \\ \vdots \\ (a_1)_{z1} \end{matrix}\right. & \begin{matrix} (a_1)_{12} \\ (a_1)_{22} \\ \vdots \\ (a_1)_{z2} \end{matrix} & \begin{matrix} \cdots \\ \cdots \\ \ddots \\ \cdots \end{matrix} & \left.\begin{matrix} (a_1)_{1z} \\ (a_1)_{2z} \\ \vdots \\ (a_1)_{zz} \end{matrix}\right] \end{matrix} \in P \\
\vdots \\
a_s = \begin{matrix} \\ (a_s)_1 \\ (a_s)_2 \\ \vdots \\ (a_s)_z \end{matrix}
\begin{matrix} (a_s)_1 & (a_s)_2 & \cdots & (a_s)_z \\ \left[\begin{matrix} (a_s)_{11} \\ (a_s)_{21} \\ \vdots \\ (a_s)_{z1} \end{matrix}\right. & \begin{matrix} (a_s)_{12} \\ (a_s)_{22} \\ \vdots \\ (a_s)_{z2} \end{matrix} & \begin{matrix} \cdots \\ \cdots \\ \ddots \\ \cdots \end{matrix} & \left.\begin{matrix} (a_s)_{1z} \\ (a_s)_{2z} \\ \vdots \\ (a_s)_{zz} \end{matrix}\right] \end{matrix} \in P
\end{gathered}
\tag{4}
$$

After determining the dependencies within the matrix, subsystem clustering can be performed, and subsystem order priorities can be confirmed. To minimize the amount of active information that affects subsequent systems, the highest level in the matrix should be used as the standard.

The h_k of QFD I is imported into the left wall of QFD II, and the relationship between ECs and CCs is evaluated (denoted as r_{kp}, $p = 1, 2, \cdots x$) by experts on a nine-point scale. The weighted CC importance i_p equation is as follows:

$$i_p = \sum_{k=1}^{n} h_k r_{kp} \tag{5}$$

When one of the CCs is related to multiple ECs, and h_k is high, i_p will be high, indicating that the component is extremely important to the engineering characteristics of the subsystem. Objects with higher impact i_p are evaluated as "promote" (i.e., options), while objects that are not promoted can maintain performance (i.e., standards). It is essential to assess whether the item is a specification system element (the element with higher sequence priority) in the integrated system architecture.

When i_{p1} and i_{p2} are similar, and $p1$ belongs to a higher-sequence-priority subsystem in the system architecture, modifying it can easily change the lower-level subsystem, resulting in a higher degree of overall customization. Consequently, it is possible to evaluate whether to maintain $p1$, improve $p2$ instead, and replace the module with its planned specification.

Then, the improvement indicators of the product's CCs will be determined and evaluated. The decision of the CC index correlates with the importance of ECs and the sequence priority in the subsystem DSM. CCs with higher importance in QFD II and higher priority in the DSM can be planned to improve performance and standardize their specifications.

Based on the QFD II integrated module structure, standard modules, optional modules, and specification upgrade modules can be defined. In the integration stage, the clustered modules in the DSM can be expanded into component modules through QFD II. CCs with high importance may exhibit high variability (influence) and complex interactions, allowing them to become independent modules of transaction specifications.

3. Case Study

The injection molding machine (IMM) is equipment used to process plastic materials to manufacture plastic products. In order to find a more reasonable process to process a variety of different plastic raw materials and develop more cost-effective products, the injection structural unit has developed different configurations of mechanisms based on corporate strategies, experience, markets, and design methods, to meet different product and cost production requirements.

Company F focuses on the research and development, manufacturing, and sales of injection molding machines. It adheres to the concept of creating high-value products, integrates globalization and diversified business strategies, and achieves the goal of permanent sustainable operation. Currently, the company needs to develop an injection molding machine, plan strategic modules in a customer-oriented manner, reduce sluggish inventory problems in the factory and facilitate maintenance and replacement, and quickly respond to market demand by improving module performance in response to dynamic changes in the market.

This study takes the injection molding machine industry product as a case study and takes the injection unit mechanism of the current market trend product (electric injection) as the research object. It integrates the design of modular architecture through QFD and DSM methods and analyzes the research process and results. It serves as an important basis and reference for the development of modular design in this research institute. The complex information flow between different perspectives of all modules is integrated into an industry-standard, customized module selection table, making the module more widely and conveniently used in industry or future technology development.

3.1. Defining Requirements and System Functions

As such, this study conducts in-depth interviews with customers who have experience using the product in the market. The expert team then summarizes their requirements based on the interview content. In this study, a total of 20 experts were invited for this study, and 12 accepted the invitation to form an expert group. These experts have at least two years of experience related to plastic molding injection, with expertise in injection machine design, plastic molding processes, and mold testing. Table 1 shows the specific information of the experts.

This study conducted an AHP matrix calculation based on the expert scores to obtain the importance ranking of CRs (Table 2). Subsequently, experts defined ECs that could satisfy CRs and evaluated the correlation scores between CRs and ECs to obtain the importance and weight of ECs. Next, experts were invited to score each CR's satisfaction after using products from F company and competitors. At this point, the QFD I quality house was completed, as shown in Figure 4.

Table 1. Basic information of experts.

Position	Seniority	Major
Organization development team leader	5 years	Development and design of injection molding machine
Injection process engineer	6 years	Injection molding machine process test
Machine test engineer	18 years	Injection molding machine testing and inspection
Institutional development engineer	4 years	Development and design of injection molding machine
Head of R&D Center	8 years	R&D of injection molding machine
Injection molding engineer	2 years	Injection molding
Injection molding engineer	10 years	Injection molding
Injection molding engineer	6 years	Injection molding
Product Development Engineer	8 years	Plastic product development
Product Development Engineer	8 years	Plastic product development
Injection molding engineer	7 years	Injection molding
Injection Molding Section Chief	19 years	Injection molding

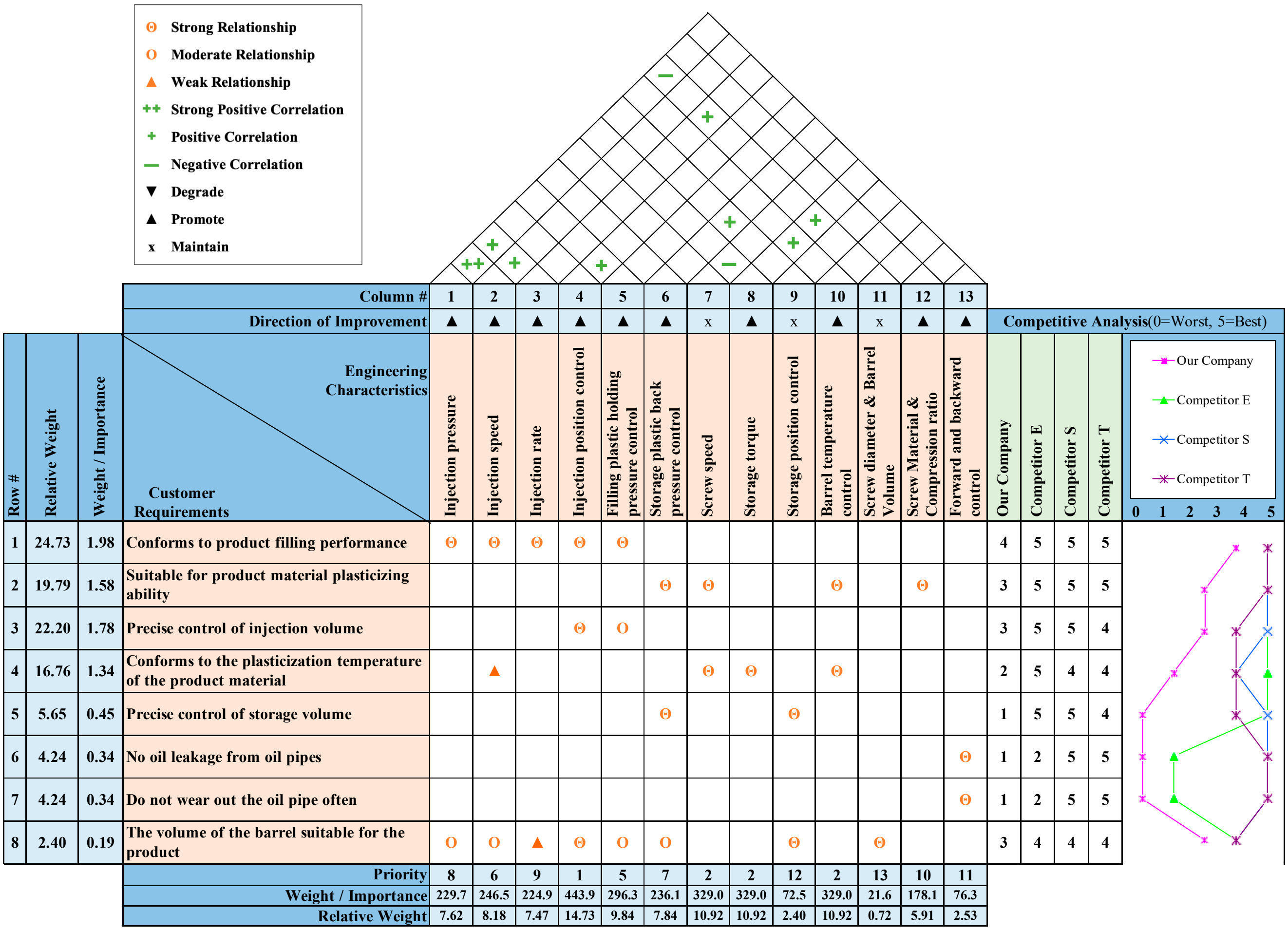
Table 2. AHP analysis matrix of CRs.

Customer Requirements	NO.	1	2	3	4	5	6	7	8	Absolute Weight	Relative Weight
The volume of the barrel suitable for the product	1	1	1/7	1/7	1/5	1/5	1/5	1/3	1/3	0.19	2.4
Conforms to product filling performance	2	7	1	3	5	1	1	7	7	1.98	24.73
Suitable for product material plasticizing ability	3	7	1/3	1	3	1/3	3	7	7	1.58	19.79
Precise control of storage volume	4	5	1/5	1/3	1	1/5	1/3	1	1	0.45	0.45
Precise control of injection volume	5	5	1	3	5	1	1	5	5	1.78	22.2
Conforms to the plasticization temperature of the product material	6	5	1	1/3	3	1	1	5	5	1.34	16.77
No oil leakage from oil pipes	7	3	1/7	1/7	1	1/5	1/5	1	1	0.34	4.23
Do not wear out the oil pipe frequently	8	3	1/7	1/7	1	1/5	1/5	1	1	0.34	4.23

3.2. Subsystem Clustering

As shown in Figure 5, experts decomposed the injection unit into subsystems with different functions. According to the relationship between subsystems, the interaction relationship was defined as the condition that affects the design between elements, as follows:

- Barrel system: barrel system design specification is defined by the customer product specification and mold specification.
- Injection system: injection system design specification is defined by the barrel system and customer product specification.
- Storage system: storage system design specification is defined by barrel system specifications and plastic properties.
- Base movement: base movement system design specification is defined by the specifications of the barrel system, injection system, and storage system.
- Heating system: heating system design specification is defined by the barrel system specifications and plastic properties.
- Feeding system: feeding system design specification is defined by the specifications of the barrel system.



Row #	Relative Weight	Weight / Importance	Customer Requirements	1	2	3	4	5	6	7	8	9	10	11	12	13	Our Company	Competitor E	Competitor S	Competitor T
1	24.73	1.98	Conforms to product filling performance	Θ	Θ	Θ	Θ	Θ									4	5	5	5
2	19.79	1.58	Suitable for product material plasticizing ability						Θ	Θ			Θ		Θ		3	5	5	5
3	22.20	1.78	Precise control of injection volume				Θ	O									3	5	5	4
4	16.76	1.34	Conforms to the plasticization temperature of the product material		▲					Θ	Θ		Θ				2	5	4	4
5	5.65	0.45	Precise control of storage volume						Θ			Θ					1	5	5	4
6	4.24	0.34	No oil leakage from oil pipes													Θ	1	2	5	5
7	4.24	0.34	Do not wear out the oil pipe often													Θ	1	2	5	5
8	2.40	0.19	The volume of the barrel suitable for the product	O	O	▲	Θ	O	O			Θ		Θ			3	4	4	4
			Priority	8	6	9	1	5	7	2	2	12	2	13	10	11				
			Weight / Importance	229.7	246.5	224.9	443.9	296.3	236.1	329.0	329.0	72.5	329.0	21.6	178.1	76.3				
			Relative Weight	7.62	8.18	7.47	14.73	9.84	7.84	10.92	10.92	2.40	10.92	0.72	5.91	2.53				

Figure 4. The result of QFD I.

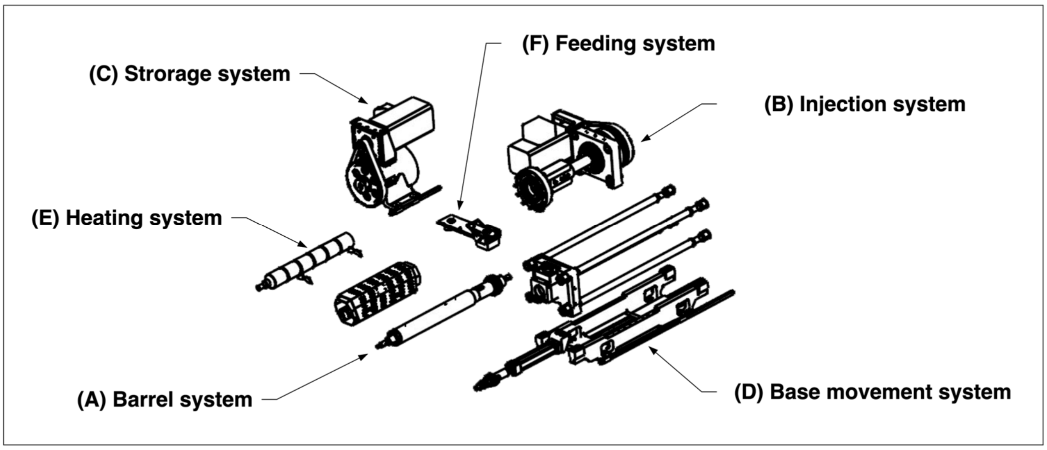


Figure 5. Exploded view of injection unit.

As shown in Figure 6, the system sequence level was divided by the DSM so that the six subsystems were carried out sequentially under ideal conditions, and finally, the clustering was performed. Since the barrel system, injection system, and storage system affected the base movement system simultaneously, they were clustered into a module system, which was defined as a standard or replacement system module.

Subsystem name	NO.	A	B	C	D	E	F
Barrel system	A						
Injection system	B	x					
Storage system	C	x					
Base movement system	D	x	x	x			
Heating system	E	x					
Feeding system	F	x					

Figure 6. DSM of the injection unit.

3.3. Integrated Subsystem Modules

As illustrated in Figure 4, the ECs of QFD I correspond to the relevant subsystems, and the subsystems marked with the weights of ECs can indicate their importance (affecting product variation). Referring to Table 2, the reasons for variation may be maintenance, optional, or improvement. If the subsystem was used as the inventory module, either subsystem E or subsystem F (with the least interaction relationship) could be selected for storage. Subsystem E needed to be evaluated by considering the extension selection conditions of ECs, while subsystem F could directly standardize the preparations or stocks. Other systems could drill down to components to assess the possibility of other component modules.

3.4. Component Clustering

As depicted in Figure 7, it was essential to minimize the coupling interaction relationship to partition the components effectively. A coupling relationship within the components implies repeated message interactions between A6, A7, and A8, which can be clustered into modules.

Components name	NO.	A5	A6	A7	A8	A1	A2	A3	A4	A9
Screw	A5									
Back flow valve	A6	x		x	x					
Backflow Ring Bushing	A7	x	x		x					
Screw tip	A8	x	x	x						
Barrel	A1	x								
Cylinder haed	A2	x				x				
Main body nozzle	A3						x			
Sub nozzle	A4							x		
Barrel nut	A9					x				

Figure 7. DSM of Barrel System.

As shown in Figure 8, an interactive relationship between B1 and B2 formed a module. (B2, B4, B3, B5, B6, B7, B8), (B4, B3, B5, B6, B7, B8, B9), and (B3, B5, B6, B7, B8, B9, B10) formed a module, which could be combined into one module (B2, B4, B3, B5, B6, B7, B8, B9, B10). This module specification interacted with B1, and B1 could be added. The clustering standard module was (B1, B2, B4, B3, B5, B6, B7, B8, B9, B10). Additionally, the two modules (B17, B18, B19) and (B11, B13) were related to B20 and were customer-required characteristic parts; they would be listed as standard modules. B12 was an independent moving part and would not be retained with the variation in specifications.

As shown in Figure 9, (C3, C4, C5, C6) and (C7, C2) had a coupling relationship. However, (C7, C2) had information input (sequential relationship) from (C3, C4, C5, C6), which could be expanded to (C3, C4, C5, C6, C7, C2). As shown in Figure 8, it was determined that the message was input from the barrel system, and it was necessary to determine whether it was a standard or optional specification module using QFD II. Both (C8, C9, C10) and (C11, C13) had messages from C1, and C1 was optional in the specification defined in Figure 4, allowing the inventory module to synchronize with C1. C12 and C14 were independent parts, which would not be retained with the variation in specifications.

Components name	NO.	B1	B2	B4	B3	B5	B6	B7	B8	B9	B10	B14	B16	B20	B15	B17	B18	B19	B11	B13	B12
Load cell	B1	■	x																		
Ball screw	B2	x	■	x		x	x	x	x												
Bearing housing body front cover	B4		x	■	x					x											
Bearing housing body	B3			x	■	x	x				x										
Ball screw bearing set	B5		x			■															
Bearing spacer	B6		x			x	■				x										
Bearing lock nuts	B7		x				x	■													
lock washers for bearings	B8							x	■												
Rotary oil seal (front cover)	B9		x							■											
Rotary oil seal (spacer)	B10					x					■										
Locking ring (ball screw)	B14		x									■									
Injection servo motor fixed base	B16				x								■								
Injection servo motor	B20													■							
Locking ring (injection motor)	B15													x	■						
Injection motor fixing plate	B17													x		■	x	x			
Injection servo motor adjustment seat	B18													x		x	■	x			
Injection motor base	B19												x	x		x	x	■			
Injection servo motor driven pulley	B11											x							■	x	
Injection servo motor dirving pulley	B13													x	x				x	■	
Injection servo motor drive belt	B12												x					x	x	x	■

Figure 8. DSM of injection system.

Components name	NO.	C1	C3	C4	C5	C6	C7	C2	C8	C9	C10	C11	C13	C12	C14
Storage Servo motor	C1	■													
Bearing shaft	C3		■	x	x	x									
Self-aligning bearings	C4		x	■											
thrust bearing	C5		x		■										
Rotary Oil Seal (Storage)	C6		x			■									
Front cover of hydraulic motor body	C7		x	x		x	■	x							
Storage motor body	C2	x	x		x		x	■							
Storage motor fixed base	C8	x							■	x	x				
Storage motor fixing plate	C9	x							x	■	x				
Storage servo motor adjustment seat	C10								x	x	■				
Storage servo motor driven pulley	C11		x									■	x		
Storage servo motor dirving pulley	C13	x										x	■		
Storage servo motor drive belt	C12							x	x			x	x	■	
Belt gear cover	C14	x											x		■

Figure 9. DSM of storage system.

The execution of division and clustering is demonstrated in Figure 10. (D1, D3) information came from the barrel system, injection system, and storage system, which were high-fluctuation clustering modules (Figure 6). D4 affected D6, D2, and D5, which could be clustered to synchronize and change. The information of D4 came from the barrel system as a specification change component.

Conponents name	NO.	D1	D3	D4	D6	D2	D5
Barrel base	D1	■	x				
Micro adjustment bolt	D3	x	■				
Pull-in cylinder assembly	D4			■			
Pull-in Cylinder connection	D6			x	■		
Pull-in Cylinder Mounts	D2	x		x		■	
Pull-in Cylinder transfer shaft	D5			x	x		■

Figure 10. DSM of base movement system.

As shown in Figure 11, it can be determined that (E1, E2, E3, E4) information came from the barrel system, and E5 and E6 were from the information of E1, E2, and E4. Thus, the barrel system was the uppermost sequential level of the subsystem and had to standardize its specifications, affecting all CCs of the heating subsystem that could be clustered into a standard modular system.

The corresponding table of feeding system components consisted of only one set of components, so there was no need to expand the DSM.

Conponents name	NO.	E1	E2	E3	E4	E5	E6
Barrel heater	E1	■					
Barrel head heater	E2		■				
Nozzle heater	E3			■			
Thermocouple	E4				■		
Barrel cover holder	E5	x	x			■	
Barrel cover set	E6	x	x		x	x	■

Figure 11. DSM of the heating system.

3.5. Defined Important System Components

The experts evaluated the correlation between ECs and CCs, obtaining the importance and weight of CCs. In this stage, the quality house of QFD II was completed and constructed, as displayed in Figure 12.

Θ	Strong Relationship	9
O	Moderate Relationship	3
▲ (orange)	Weak Relationship	1
▼	Degrade	
▲	Promote	
x	Maintain	

Row #	Relative Weight	Weight / Importance	Engineering Characteristics \ Characteristics	Screw	Nozzle	Barrel	Thermocouple	Heater bands	Pull-in cylinder	Feed hopper	Load cell	Storage servo motor	Storage driven pulley	Storage dirving pulley	Ball screw	Injection servo motor	Injection driven pulley	Injection dirving pulley	Engineering direction
			Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
			Direction of Improvement	▲	▲	x	x	▲	▲	x	▲	▲	▲	x	▲	▲	▲	x	
1	7.62	230	Injection pressure	Θ	O				Θ		Θ				Θ	Θ	Θ	Θ	▲
2	8.18	246	Injection speed												Θ	Θ	Θ	Θ	▲
3	7.47	225	Injection rate	Θ	O										Θ	Θ	Θ	Θ	▲
4	14.73	444	Injection position control													Θ			▲
5	9.84	296	Filling plastic holding pressure control								Θ					Θ			▲
6	7.84	236	Storage plastic back pressure control								Θ					Θ			▲
7	10.92	329	Screw speed									Θ	Θ	Θ					x
8	10.92	329	Storage torque									Θ	Θ	Θ					▲
9	2.40	72	Storage position control									O				Θ			x
10	10.92	329	Barrel temperature control			Θ	Θ	Θ											▲
11	0.72	22	Screw diameter & Barrel Volume	Θ		Θ				O									x
12	5.91	178	Screw Material & Compression ratio	Θ		▲ (orange)													▲
13	2.53	76	Forward and backward control						Θ										▲
			Priority	9	14	10	11	11	13	15	2	6	7	7	3	1	3	3	
			Weight / Importance	195	45	111	98	98	91	2	228	204	197	197	209	523	209	209	
			Relative Weight	7.47	1.73	4.23	3.75	3.75	3.49	0.08	8.70	7.79	7.51	7.51	8.00	19.98	8.00	8.00	

Figure 12. The result of QFD II.

CCs will influence the standard, option, and even the upgrade of modules. They were obtained by expanding ECs from CRs of QFD I, so regardless of their importance and weight, they are all elements in satisfying CRs. Less important CCs can maintain specifications but must also consider the planning of their inventory and replacement. Therefore, in the subsequent integration steps, each CC needed to be planned for its purpose under the module architecture.

3.6. Integrate Component Modules

The objective of this stage was to integrate the modularization of components within the subsystem and determine whether the component structure matrix clustering expands into optional modules, standard modules, or improvement module specifications through QFD II.

3.6.1. Barrel System

A5 (7.47%) was an essential CC in QFD II and represented a crucial requirement specification at the top level of the system. The requirements of screw material and screw compression ratio, screw diameter, and barrel volume could be defined as the optional specification standard module of the barrel system.

The corresponding requirements of A1 (4.22%) were the screw diameter and barrel volume (defined as maintenance), and there was an input message from A5. Thus, its module was defined as a standard specification and included in the A5 module. Its internal A4 (1.73%) was defined as an improvement, indicating that customers could choose to replace it. Since there were no other specification requirements to input, it remained independent as a changeable part.

3.6.2. Injection System

B2 (8.01%) appeared in clusters (B1, B2) and (B2, B4, B3, B5, B6, B7, B8) simultaneously. Within the modular architecture, B2 was elevated to the next level. B1 (8.7%) and B2 (8.01%) influenced each other, and the modules could be clustered into standard, optional, or improvement specifications. Since B9 and B10 were not present in QFD II, and B14 was not coupled with the information originating from B2, the module could be expanded as (B2, B1, B4, B3, B5, B6, B7, B8, B9, B10, B14). The corresponding ECs of this module included holding pressure control (9.85%), back pressure control (7.82%), injection speed (8.19%), injection pressure (7.63%), and injection rate (7.48%). B16's independent main factors were messages output to the cluster (B17, B18, B19) and the independent part B12.

B20 (21.06%) output messages to B15 and (B17, B18, B19), which could be expanded into modules (B20, B15, B17, B18, B19). This module could be standard, optional, or improved. The corresponding ECs included injection position control (14.76%), pressure holding control (9.85%), back pressure control (7.82%), injection speed (8.19%), injection pressure (7.63%), and injection rate (7.48%).

There was a coupling relationship between B11 (8.01%) and B13 (8.01%). Since B13 received information input from B20 components with higher weight requirements and had the same weight as B11, it was maintained as a standard, while B11 specifications were improved and modified to reduce interaction. This module could be standard or optional, and its corresponding ECs included injection speed (8.19%), injection pressure (7.63%), and injection rate (7.48%). B12 had information from two modules and a discrete part and was classified as a discrete independent part.

3.6.3. Storage System

C1 (7.78%) influenced two clusters (C8, C9, C10) and (C11, C13). Among them, the cluster (C8, C9, C10) appeared in QFD II, and its module could be (C1, C8, C9, C10). This module satisfied the ECs: storage torque (10.91%), screw speed (10.91%), and storage position control (2.39%). Clusters (C3, C4, C5, C6) and (C7, C2) were not included in QFD II. They could be expanded and clustered into the stock motor base module. It was verified that C3 (bearing shaft) was the top-level component, and its information originated from the barrel system specification (Figure 8), allowing its module to relate to the barrel system with the same standard specification.

There was a coupling relationship between C11 (7.5%) and C13 (7.5%). Since C13 received information input from C1 and had the same weight as C11, it was maintained as a standard, and C11's specification was improved to reduce interaction variation. This module could be standard or optional, with corresponding customer requirements being storage torque (10.91%), screw speed (10.91%), and storage position control (2.39%). C12 had information from three modules, and C14 had information from two modules, leading to their classification as independent parts.

3.6.4. Base Movement System

The cluster (D1, D3) was the top-level module of this system, with D1's information originating from systems A, B, and C, and the interaction relationship depicted in Figure 8. D4 (3.5%) provided the EC output message to D6, D2, and D5, and its components were modularized. The D4 message came from subsystem A (Figure 8), allowing its module to share the same standard specification as subsystem A. The corresponding ECs were the electric control of seat advance and retreat (2.54%). If customers chose to improve performance, the entire set of replacement seat advance and retreat electric mechanisms could be replaced. Alternatively, if cost was a concern, the standard hydraulic seat advance and retreat cylinder mechanism could be maintained.

The modules in this system received input from other system information (Figure 8), indicating that this system was a system of change specifications. In cases of a very high degree of change, this system could not be prepared or stocked, posing a risk of unusable changes or stagnant materials.

3.6.5. Heating System

E1, E2, and E3 belonged to the heater group (weighted 3.75%), and the information for E1, E2, and E3 all originated from subsystem A (Figure 8). Consequently, the module could share the same standard specification as subsystem A, with its corresponding EC being the temperature control of the barrel. E4 belonged to the electric heating induction line alone (weight 3.75%), representing a commercially available specification. It could be replaced with a lifting function specification separately, with the corresponding EC being the temperature control of the material tube. E5 and E6 both received information from the cluster (E1, E2, E3), and upgrading specifications would involve replacing them with different styles, but this would not affect the higher-order sequence-level parts.

3.6.6. Feeding System

This system consisted of F1 (0.08%) as a single component. The corresponding EC was the screw outer diameter (0.71%) (to be maintained), so it was listed as a module that maintained the standard specification.

Based on the above analysis and design strategy, Company F created one modular product to meet the market demand and design objectives. The detailed exploded view of the product is shown in Figure 13.

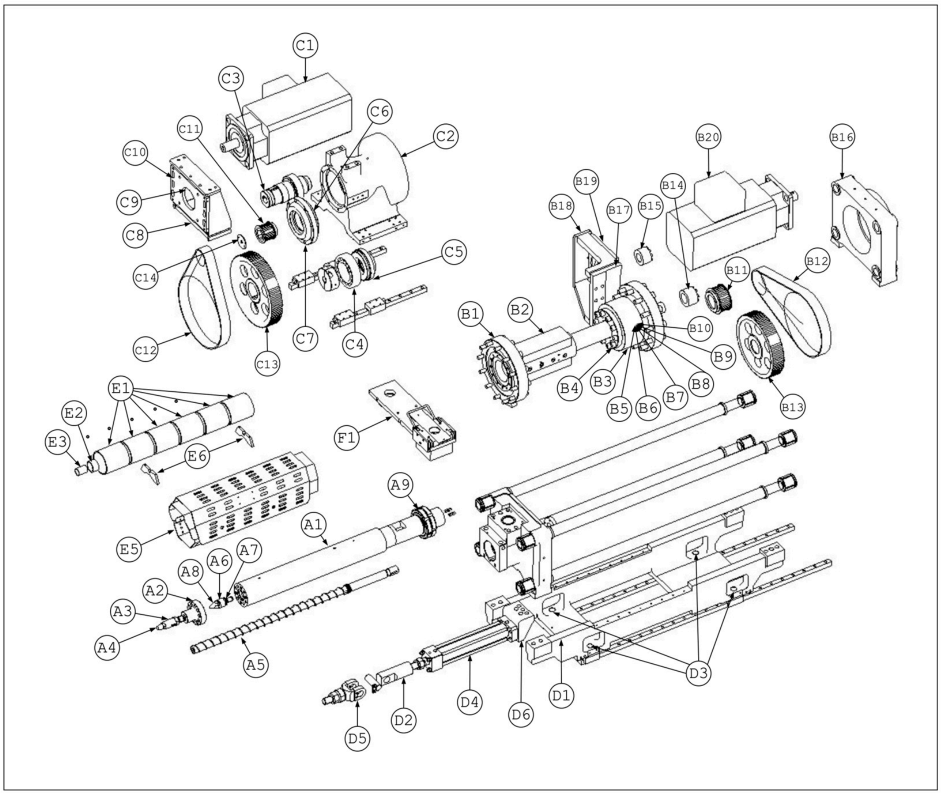


Figure 13. Exploded view of the injection system components.

4. Discussion

This study first emphasizes the importance of the first stage as the initial point of conversion, highlighting the need for expert advice to fully satisfy customer requirements for the purpose of module design planning. Module requirement functions and applicability metrics were clarified using QFD I and II based on the rationalization mechanism of HOQ. The partitioning and clustering of subsystems and components using the DSM methodology simplifies the complexity of the modules and ensures the proper categorization and sequencing of the system.

Several tasks were involved in QFD I to evaluate reasonableness and appropriateness. The first task was the assessment of ECs. As previously mentioned, if the additional objectives of the module were not defined during the interview in the requirements phase, there might be no corresponding ECs in the evaluation, which would inevitably be unreasonable and require review. The second task was a competitive assessment, aimed at analyzing product competitors through customer evaluations, comparing product satisfaction levels, and defining development goals. The third task was the assessment of engineering conflicts. Implementing this assessment required confirmation that ECs were necessary; otherwise, assessing in an unreasonable state would only serve as an indicator of appropriateness. Engineering conflicts allowed experts to evaluate the suitability of goals more carefully to achieve product development objectives. As a result, the importance of ECs not only indicated significance but also enabled the use of the importance concept to compare costs and determine industry satisfaction from a strategic thinking perspective.

In phase 2, QFD II provided a more detailed development of ECs that satisfied CRs and developed corresponding CCs. This meant that these CCs all met the CRs. Additionally, an evaluation mechanism was in place to ensure the components' correspondence, ensuring their rationality. QFD I and II explicitly defined the module function and the suitability index according to the rationality mechanism in the HOQ.

This study employed the DSM to partition and cluster subsystems and components. Firstly, defining functions from the system simplified the complexity of the module. Then, these functions could be classified, but the system sequence still needed to be defined. This was mainly because significant specifications between systems had to meet certain specifications, and the latter would change due to alterations in the former. Engineering characteristics in QFD I included the main specification demand and the specification system. If the same influence relationship was classified into the same module between different systems, the module's complexity would lead to an extensive range of modules. If there was element variation within the subsystem, it could result in the risk of design changes and inventory issues. The benefit of independent specification engineering was to minimize the impact on internal modules. If the clustered system was a system module of the required specification, it would typically be used for mass production, and employing the exact specification would be more suitable for industries with low customization.

In the DSM, when the relevant accessories participate in the important parts of QFD II, they will be expanded and aggregated by the related clustering modules, which results in a meaning of clustering that is distinct from the original interaction relationship. The interaction relationship should be clustered into modules, and these modules cannot be independent. In this study, the required parts are clustered into specification modules, and when they do not conflict with other specifications, they can be expanded and aggregated with module components. However, when a component is at the lowest level of the DSM and is subject to multiple specifications, it may become a separate module or component. In such cases, it is not advisable to stock these components due to the high likelihood of change, which makes them susceptible to the risks of design alterations and inventory retention.

This research began by emphasizing the importance of phase 1 as the initial point of conversion, highlighting the need for expert opinions to fully meet customer requirements and achieve the purpose of module design planning. QFD I and II were utilized to clearly define the module function and the suitability index according to the rationality mechanism in the HOQ. The DSM method was employed to partition and cluster subsystems and components, simplifying the complexity of the module and ensuring the proper classification and sequencing of systems.

5. Limitations and Future Research

While our study effectively demonstrates the proposed approach and highlights its novelty in both theoretical and practical contexts, it is important to acknowledge several limitations that warrant consideration.

Firstly, the evaluation of economic and environmental benefits associated with the implemented approach may be constrained by data availability. As such, we acknowledge that our study may not provide a comprehensive assessment of the economic and environmental impacts of the proposed module design planning method. Future research endeavors should aim to address this limitation by incorporating more extensive data collection efforts and robust analytical frameworks to enable a more precise evaluation of the economic and environmental benefits.

Secondly, despite our efforts to minimize biases and subjectivity in the decision-making process, the reliance on expert opinions and input may introduce inherent limitations. The subjective nature of expert judgments could potentially influence the outcomes of the module design planning process, thereby impacting the validity and reliability of our findings. Future studies could explore alternative methodologies or validation techniques to enhance the objectivity and robustness of the decision-making process.

Lastly, while our study focuses on integrating quality function deployment (QFD) and Design Structure Matrix (DSM) methodologies for module design planning, we acknowledge that there may exist alternative or complementary approaches that could offer additional insights or improvements. However, due to the scope and objectives of our research, we were unable to explore the full spectrum of available methodologies. Future investigations could consider incorporating alternative decision-making frameworks or algorithmic models to provide a more comprehensive understanding of module design optimization.

In light of the aforementioned limitations, there is ample scope for further research in this area. One promising avenue for future exploration could involve the development and validation of new models or algorithms for module design planning. By leveraging advances in computational methods and data analytics, researchers could devise innovative approaches to optimize module configurations and enhance product customization while addressing key constraints such as cost, time, and resource efficiency. Integrating cutting-edge technologies such as artificial intelligence and machine learning algorithms could enable the development of more adaptive and predictive module design solutions, paving the way for enhanced competitiveness and sustainability in manufacturing industries.

6. Conclusions

This study aimed to develop a comprehensive approach to module design planning by integrating QFD and DSM methodologies. This research presented a systematic process to assess the reasonableness and appropriateness of product design while satisfying customer requirements and minimizing engineering conflicts. The result demonstrated that it can significantly streamline the module design process and facilitate better decision making in product development, offering a clear and systematic approach to module design planning, helping companies better understand and address customer requirements, and leading to increased product satisfaction and competitiveness in the market.

The innovative contribution of this research can be summarized in two aspects: From a methodological perspective, the proposed decision-making method aids in analyzing the uncertainty of customer needs and addressing coupling problems in complex engineering. From a practical standpoint, the developed comprehensive decision-making model can assist management stakeholders in gaining a better understanding of the entire process of product module evaluation and selection from the perspective of user needs. This can help shorten product development time, reduce design changes, lower product inventory and development costs, and promote sustainable industrial development. Specifically, the contributions of this study are as follows:

(1) In-depth understanding of market demands, enabling the early consideration of customer needs and changes in product development planning to match market demands and reduce frequent design changes and product maintenance difficulties.

(2) Customer-oriented strategic module planning, reducing factory inventory backlog issues and facilitating maintenance and replacement.

(3) Designing a product modular structure, allowing engineers to effectively integrate product configurations, shorten custom development design time, increase delivery rates, and respond rapidly to market demands by enhancing module performance in response to dynamic market changes.

(4) Validating the effectiveness of the proposed method through practical case studies, and combining QFD and the DSM to plan module frameworks, assisting products in adapting to different customization conditions and demands in the market, and developing various planning module approaches.

This study focuses on the module planning of large electromechanical products as a research case. The improved method offers a comprehensive, precise, and effective decision-making approach for evaluating and selecting module development in large electromechanical products, laying a robust foundation for the modular and standardized strategic design of future large electromechanical products.

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