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Maintenance Service Configuration Optimization for Complex Equipment

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Abstract: Maintenance activities mostly depend on the specific conditions of individual equipment, being defined as personalized businesses. In order to improve the efficiency of maintenance activities for complex equipment in lots, the thinking of mass customization is used. After the modular technology used for generic maintenance model, the product/service was divided into mandatory and optional modules, which can form multiple optional maintenance service solutions. Considering the characteristics of maintenance activities and customers' personalized maintenance requirements, configuration optimization is used to find the most satisfied maintenance solution under different objectives. This paper aims to provide the configuration optimization ideas and solutions for complex equipment maintenance services. A multi-objective optimization model was established, and an algorithm based on Non-Dominated Sorting Genetic Algorithms (NSGA-II) was proposed to solve this configuration optimization model. Finally, the maintenance service of the Electric Multiple Units (EMU) bogie was taken as an example to verify the feasibility of the model and the algorithm.

Keywords: configuration optimization; maintenance service; complex equipment; multi-objective optimization; NSGA-II

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1. Introduction

Maintenance of complex equipment usually involves many levels and complex process. The scope and depth of parts and components under different maintenance levels are different. However, the same products series are similar in the maintenance scope and depth. When there is a big equipment market or this equipment has many similar sub-structures, the maintenance activities of this kind of complex equipment are usually performed in lots. Different from the process of production in lots, maintenance activities cannot be performed standardly as the production process due to the different equipment states and sub-structures. The various operational environment and users make the equipment states vary in maintenance activities, which forms the individual maintenance requirements for every equipment or parts. Therefore, different equipment may have different maintenance scope and maintenance depth, leading to the personalized needs in the selection of spare parts, optional configuration service, and upgrade service. This personalized characteristic makes it difficult to execute maintenance activities in lots. Hence, how to realize the scale efficiency and personalized service at the same time when facing a lot of equipment maintenance demands is a realistic problem to be solved. This kind of problem is called a mass personalized problem.

The mass personalized thinking in equipment maintenance activities can draw lessons from the product family design theory, using the similarity principle and modularization technology to establish a general maintenance structure model for the same product family or similar equipment. As the modularization theory is relatively mature, this paper mainly focuses on the maintenance service configuration research. Compared to the configuration research in product design and production phase, the personalized characteristics of maintenance depend not only on customers' demand, but also on the equipment/part state, and the objective of configuration is different.

Product configuration is one of the main technologies in the realization of Mass Customization [1], and domestic and foreign scholars have long carried out research on product configuration. To achieve effective competition in the global market, manufacturers must pay attention to customer needs [2], and configuration design can quickly respond to customers' personalized needs [3]. Shao et al. [4] focused on requirement configuration and a dependency analysis approach was proposed and implemented to link customer groups with clusters of product specifications. Product service configuration rules are an important part of product service configuration knowledge and an important link between customer knowledge (demand expression) and service knowledge (design parameters) [2]. Complex equipment has a complex structure and strong coupling between modules, which directly affects the efficiency and accuracy of configuration solutions. Hapsari et al. [5] studied the optimal configuration of liquid steel production under the condition of multiple objectives. Malekimajd M et al. [6] established a linear programming model, which can minimize the cost of cloud resources, reject the execution of operations belonging to multiple classes, and provide a deadline guarantee. Badurdeen et al. [7] considered the recyclability of product modules and used multi-objective optimization to optimize product configuration decisions from the perspective of sustainability of product life cycle. With the rise of service-oriented manufacturing, researchers began to combine products and services to research configuration design. Costa et al. [8] established a service resource configuration model based on product after-sales service; Cao et al. [9] established a service selection and configuration model and optimized the model based on time, cost, quality, and service. Product modularization promotes the development of intelligent design and manufacturing [10]. The configuration process cannot be separated from modular design. Modularity is driven by customer demand [11]. The correlation between parts in different product modules should be as low as possible [12]. LI et al. [13] divide the modules from optimization objectives that the correlation degree of components in the module is as high as possible and the correlation degree between modules is as small as possible. ALPARSLAN [14] proposed a multi-objective optimization framework to support the partition of interaction set modules. On the basis of module division, Sheng et al. [15] proposed the optimization method of PSS scheme configuration based on genetic algorithm, taking customer satisfaction, service quality, and service cost as the objective function, and solved it by traditional linear weighting method. As an intangible service that can help enterprises gain competitive advantage, the added value generated by maintenance can make users willing to pay fees beyond the reasonable range on a rational basis [16]. Shen et al. [17] analyzed the cost elements of PSS and estimated the configuration scheme through the activity-based costing method, so as to achieve more accurate cost comparison of the configuration scheme. In the light of the multi-objective programming problems, Sirbiladze et al. [18] presented a new two-stage possibilistic bi-criteria optimization approach to solve the VRP under extreme conditions. Harish et al. [19] introduced a concept of multi-objective nonlinear programming problem with rough parameters (R-MONLP) in the constraint set. Modu et al. [20] developed a multiobjective mathematical programming model for waste evacuation and disposal, considering the benefits of reusing/recycling recovered waste materials. Harish et al. [21] proposed an algorithm for rough multiobjective transportation problem (RMOTP) in which the cost of transportation, the source and destination parameters have been considered as rough interval parameters. There is relatively little research on the maintenance service configuration, and Sun et al. [22] proposed the configuration method of aero-engine maintenance service, which matches the maintenance services with service providers to minimize the service cost, completion time deviation, and energy consumption. Zhu [23] and Marchi [24] studied the establishment of group maintenance and opportunity maintenance models for parts with different maintenance strategies. Compared with the configuration optimization in manufacturing, maintenance service configuration optimization pays more attention to the maintenance quality and time. At the same time, there are also differences in the configuration rules. Until now, there is a lack of research on the equipment maintenance service configuration optimization combined with the maintenance service characteristics and customers' personalized needs.

This paper considers the characteristics of maintenance service and the personalized needs of customers, and applies prospect theory to quantify customer needs, it is valuable to handle maintenance service configuration optimization problem of complex equipment. Based on the configuration optimization theory, using modular technology management modules and following certain configuration rules, this paper proposes a multi-objective optimization method based on products and services for the maintenance service configuration problem of complex equipment, and establishes a multi-objective optimization model considering the scheme performance, cost, response time and module dependency, and mutual exclusion constraints in the configuration process. The configuration optimization scheme maximizes the satisfaction of customer needs and enterprise interests. This represents a novel contribution to the configuration optimization field and maintenance service.

The maintenance service configuration optimization is oriented to the complex mapping space with nonlinearity, multi-constraints, and high dimensions. Its essence is to optimize the product/service modules to meet the needs of customers and the interests of enterprises. The configuration optimization scheme provides information input and a decision-making basis for the maintenance plan to avoid the blindness of on-site decision-making. At the same time, it can reduce costs and improve efficiency, which is significant to lean maintenance. Based on the configuration optimization theory, this paper uses modular technology to manage modules, and follows specific configuration rules. Based on considering the maintenance characteristics, aiming at the service configuration optimization problem of complex equipment maintenance, this paper puts forward a multi-objective optimization configuration method based on products and services, establishes a multi-objective optimization model and solves it with Non-Dominated Sorting Genetic Algorithms (NSGA-II). Finally, the feasibility of the model and algorithm is verified by taking the Electric Multiple Units (EMUs) bogie maintenance service as an example.

2. Problem Description and Model Construction

The maintenance service configuration optimization problem involves the maintenance service and components selection. Compared with product configuration in design and manufacturing phase, configuration optimization in maintenance pays more attention to maintenance quality and maintenance time. Usually, different parts have different maintenance strategies, includes preventive maintenance, condition-based maintenance and failure-based maintenance. For high price interchangeable parts, the turnover parts or new parts will be selected according to the remaining life, inventory cycle, maintenance interval and technical parameters. At the same time, there are constraints or rules for module combination and parts choosing. Thus, the maintenance service model mainly considers the realization of customer requirements and providing solutions under the constraint of configuration rules.

2.1. Product and Service Modularization

From the perspective of customers' personalized needs and service experience, the service module and physical product module are obtained. Considering performance, cost, time, and other factors, the module design is based on the perspective of service providers to ensure the balance of interests between customers and service providers. The modularization process is shown in Figure 1.

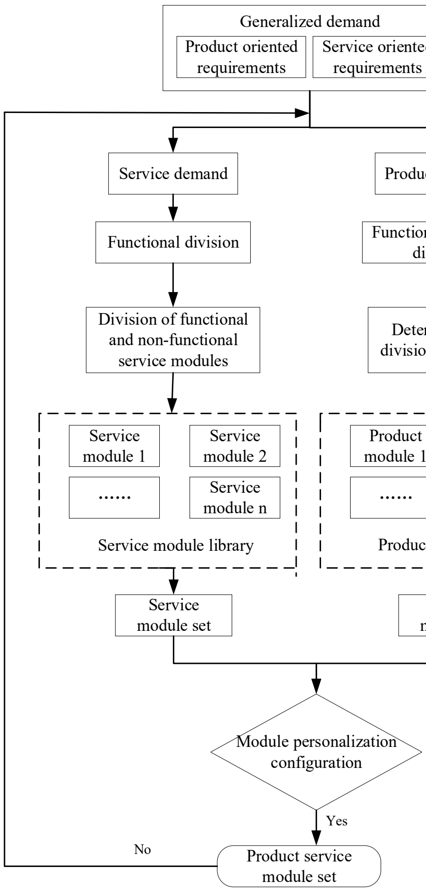

Figure 1. Product and service modularization process diagram.

The attribute correlation between product modules and service modules contributes to product service solutions. By distinguishing different tecthe technical characteristics of products a and attributes of modules, different module instances can be obtained. Modules are divided into mandatory and optional modules to meet the personalized needs of customers.

2.2. Customer Requirements Mapping

The configuration process is as follows. After receiving the maintenance order, the enterprise selects and configures the modules according to the customer's needs. Firstly, according to the prospect theory, the customer maintenance requirements are transformed into the weight of technical characteristics, and then transformed into the weight of module instances through the correlation matrix for technical characteristics and module instances. The matrix is used to measure the performance of the scheme. The higher the weight, the better the performance of the scheme. Secondly, the cost and response time are minimized to obtain a better service configuration scheme. In the service configuration process, in addition to mandatory modules, there are optional modules for customers to choose, and select a module instance for each selected module. The scheme cost should be lower than the customers' affordable price, and the service response time should be lower than the customers' maximum waiting time. Thirdly, the configuration rules need to be followed in the configuration process: module instances Mijk and Mi'j'k' are mutually exclusive. They cannot coexist simultaneously. If one is chosen, the other cannot be chosen. Module instances Mijk and Mi'j'k' coexist simultaneously. If one is chosen, the other must also be chosen.

To sum up, service scheme configuration optimization can be described as follows: the total number of modules in the mandatory module set is H1, and the total number of modules in the optional module set is H2. When the constraints are met, H1 modules are selected from the required module set, Q (Q ≤ H2) modules are chosen from the optional module set, and then a module instance is selected from the selected modules to form a service scheme.

2.3. Parameter and Set Description

'i' is used to distinguish between mandatory modules and optional modules, 'i = 1' indicates mandatory modules, including modules 1, 2, . . . , M_1, and 'i = 2' indicates optional modules, including modules 1, 2, . . . , M_2; 'j' means to select the j-th module; 'k' means to select the k-th module instance.

'c_{ij}' represents the total number of instances contained in the j-th module of the i module, 'M_{ijk}' represents the k-th instance of the j-th module of the i module, 'C_{ijk}' means the cost of the k-th module instance of the j-th module in the i module, and 'T_{ijk}' represents the response time of the k-th module instance of the j-th module in the i module. '$M_{I\text{-}TA}$' represents the correlation matrix between the module and the technical characteristics, and 'α' is the expected profit margin of the manufacturing enterprise. 'C_s' is the cost of the configuration scheme, 'C_m' is the maximum price acceptable to the customer, 'T_s' is the response time of the configuration scheme, and 'T_m' is the maximum waiting time of the customer.

'S' is the configuration scheme, and the selected configuration results are as follows:

$$S = \{[I_{11}, I_{12}, \ldots, I_{1H1}], [I_{21}, I_{22}, \ldots, I_{2H2}]\} \quad (1)$$

The cost matrix of the scheme is:

$$C = \left\{\left[C_{111}, C_{112}, \ \ldots, C_{1jk}\right], \ \left[C_{211}, C_{212}, \ \ldots, C_{2jk}\right]\right\} \quad (2)$$

The service response time matrix of the scheme is:

$$T = \left\{\left[T_{111}, T_{112}, \ \ldots, T_{1jk}\right]\right\}, \ \left[T_{211}, T_{212}, \ \ldots, T_{2jk}\right]\right\} \quad (3)$$

2.4. Decision Variables

The decision variable is y_{ijk}, a 0–1 binary decision variable, indicating whether the module instance is selected. When y_{ijk} = 1, the k-th instance of the j-th module participates in scheme selection. When y_{ijk} =0, the module instance does not participate in the selection, where i = 1, 2.

$$y_{ijk} = \begin{cases} 1, \text{The k-th instance of the j-th module of i module is selected} \\ 0, \text{The k-th instance of the j-th module of i module is not selected} \end{cases} \quad (4)$$

2.5. Model Establishment

Customers rank the technical characteristics according to their own needs, and use the prospect theory [25] to transform them into the weight vector $W_{TA} = [W_{TA1}, W_{TA2}, \ldots, W_{TAn}]$ of the technical characteristics of products and services. Assuming that there is a recognized worst-case option for technical characteristics and a total of n−1 actual technical characteristics, the initial matrix of technical characteristics is W of 1× n, select $d_{ki} = 1$ as the advantage reference point and $d_{ki} = n$ as the disadvantage reference point respectively. The loss value of the technical characteristic i selected by the customer k relative to the reference point $d_{ki} = 1$ is:

$$l_{ki} = \frac{d_{ki} - 1}{n - 1} \quad (5)$$

The return value relative to the reference point $d_{ki} = n$ is:

$$g_{ki} = \frac{m - d_{ki}}{n - 1} \quad (6)$$

Establish the loss matrix $L = [l_{ki}]$ of the customer relative to the reference point $d_{ki} = 1$ and the income matrix $G = [g_{ki}]$ relative to the reference point $d_{ki} = n$, and establish the prospect matrix $V_L = [v^1_{ki}]$ for the loss according to the loss matrix, where v^1_{ki} is the loss prospect value of the *i*-th technical feature selected by the user *k*:

$$v^1_{ki} = -\lambda (l_{ki})^{\beta}, i \in [1, n] \tag{7}$$

Similarly, for the prospect matrix $V_G = [v^m_{ki}]$ of income:

$$v^m_{ki} = (g_{ki})^{\alpha}, i \in [1, n] \tag{8}$$

Combining the loss prospect value and income prospect value, calculate the prospect value of the technical feature i selected by the customer k:

$$v_{ki} = v^1_{ki} + v^m_{ki} \tag{9}$$

After normalization, the normalized foreground value v'_{ki} and the weight vector $W_{TA} = [W_{TA1}, W_{TA2}, \ldots, W_{TAn}]$ of the technical characteristic *i* selected by the customer *k* are obtained.

$$v'_{ki} = \frac{v_{ki} - \min(v_{ki})}{\max(v_{ki}) - \min(v_{ki})} \tag{10}$$

$$W_{TAi} = \frac{v'_{ki}}{\sum_k \sum_i v'_{ki}} \tag{11}$$

The customer demand is transformed into the weight of technical characteristics through prospect theory, and into the weight of module instances through the correlation matrix between technical characteristics and module instances, as shown in the following formula.

$$\begin{aligned}
M_{I-TA} &= \begin{bmatrix} M_{1,I-TA} \\ M_{2,I-TA} \end{bmatrix}_{(\sum_{i=1}^{2}\sum_{j=1}^{H_i} C_{ij}) \times p} \\
D &= M_{I-TA} \times W_{TA} \\
M_{1,I-TA} &= \begin{pmatrix} \gamma_{1111} & \cdots & \gamma_{111p} \\ \vdots & \ddots & \vdots \\ \gamma_{1H_1C_{1H_1}1} & \cdots & \gamma_{1H_1C_{1H_1}p} \end{pmatrix} \\
M_{2,I-TA} &= \begin{pmatrix} \gamma_{1111} & \cdots & \gamma_{111p} \\ \vdots & \ddots & \vdots \\ \gamma_{1H_2C_{1H_2}1} & \cdots & \gamma_{1H_2C_{1H_2}p} \end{pmatrix}
\end{aligned} \tag{12}$$

To sum up, the mathematical model of service scheme configuration optimization can be expressed as:

$$\max F = \sum_{i=1}^{2}\sum_{j=1}^{H_i}\sum_{k=1}^{C_{ij}} \left[y_{ijk} \left(\sum_{l=1}^{p} \gamma_{ijkl} W_{TAl} \right) \right] \tag{13}$$

$$\min C = \sum_{i=1}^{2}\sum_{j=1}^{H_i}\sum_{k=1}^{c_{ij}} y_{ijk} C_{ijk} \tag{14}$$

$$\min T = \sum_{i=1}^{2}\sum_{j=1}^{H_i}\sum_{k=1}^{c_{ij}} y_{ijk} T_{ijk} \tag{15}$$

$$C_s(1+\alpha) \le C_m, T_s \le T_m \tag{16}$$

$$\sum_{j=1}^{H_1} y_{1jk} = H_1, \sum_{j=1}^{H_2} y_{2jk} \le H_2 \tag{17}$$

$$\sum_{k=1}^{c_{ij}} y_{ijk} = 1, i = 1; \sum_{k=1}^{c_{ij}} y_{ijk} \leq 1, i = 2 \quad (18)$$

$$G_{ijk-i'j'k'} = \begin{cases} 1, if\ M_{ijk}\ and\ M_{i'j'k'} \text{ are } compatible \\ 0,\ if\ M_{ijk}\ and\ M_{i'j'k'} \text{ are } exclusive \end{cases} \quad (19)$$

Among them, Formula (13) represents the maximization of the module instance weight, which is used to measure the overall performance of the scheme; Formula (14) represents the minimization of the total cost; Formula (15) represents the minimization of the total response time; Formula (16) represents cost and time constraints; Formula (17) means that the mandatory module must be selected, and the optional module is selected by the customer; Formula (18) indicates that each selected module needs to choose a module instance; and Formula (19) uses the variable '$G_{ijk\text{-}i'j'k'}$' to express the relationship constraints between modules.

3. Case Analysis and Solution

3.1. Case Description

SF enterprise is the industrialization base of high-speed trains. At present, it has formed a series of Electric Multiple Units (EMUs) products with different speed levels and different train formation forms. It provides depot repair, cooperative repair, and parts supply. The process of maintenance, repair and overhaul (MRO) service is shown in Figure 2.

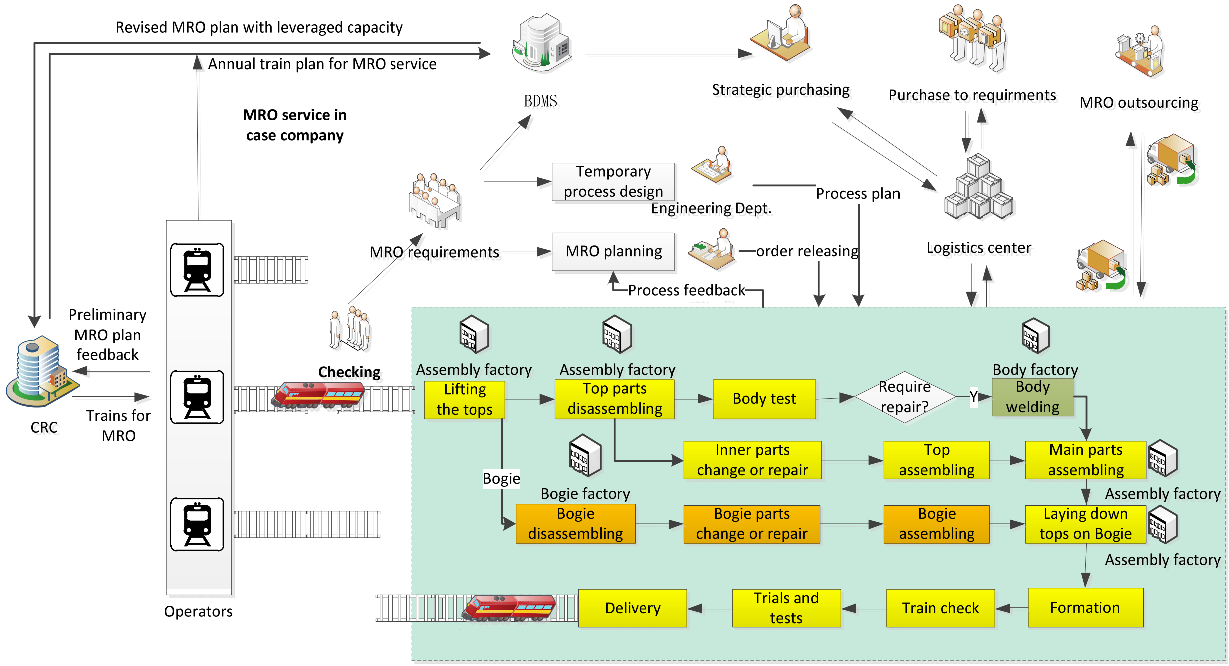

Figure 2. The process of MRO service.

As shown in the above figure, after confirming the vehicle, the enterprise clarifies the customers' needs and performs the Electric Multiple Units (EMUs) maintenance. Electric Multiple Units (EMUs) maintenance is complex system maintenance, which is carried out according to the actual state. The maintenance content, strategy, and time corresponding to different maintenance levels are different, and the configuration of different levels is the configuration of services. The essence of maintenance service configuration optimization is to select product modules and service modules, maximize customer needs and enterprise interests, and provide the necessary guarantee for achieving a win–win.

The bogie is an important part of the Electric Multiple Units (EMU) as a supporting running device that enables the EMU to run along the track. The elemental composition of a bogie includes frame, wheelset, axle box, suspension device, brake device, drive device, etc. The configuration optimization of bogie maintenance service provides a configuration scheme for customers after clarifying their needs. According to the enterprise maintenance background and historical data, the service modules and product modules can be obtained. Different module instances can be selected under different modules. The service module set and product module set are shown in Figures 3 and 4.

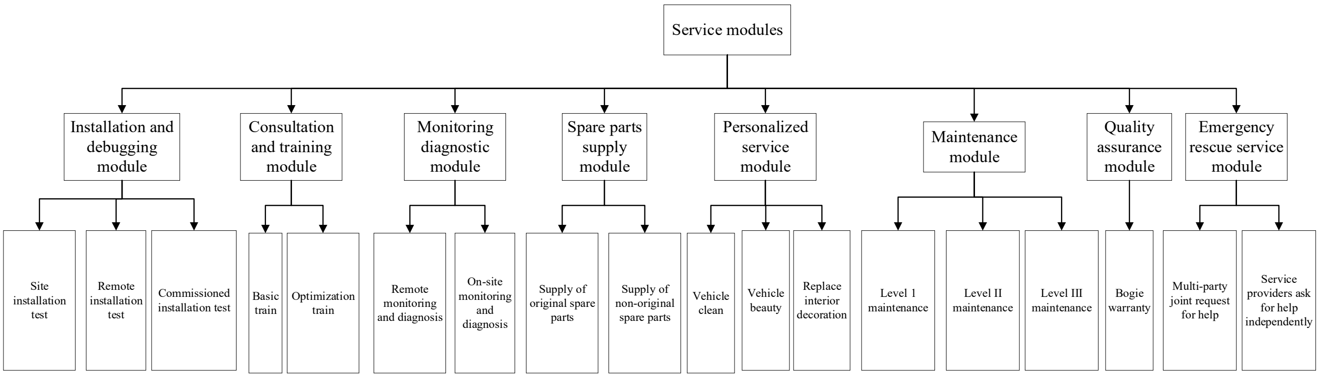

Figure 3. Service module set.

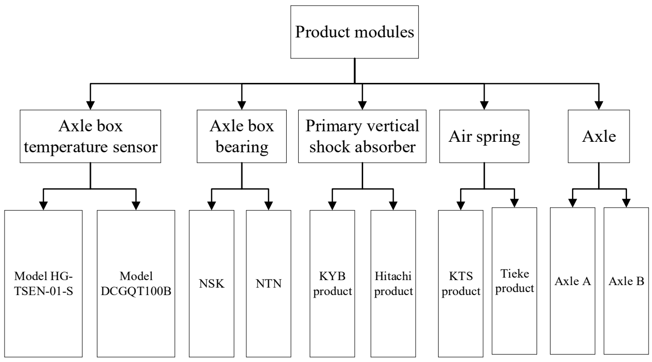

Figure 4. Product module set.

After receiving the order, the enterprise selects and configures modules according to the customers' needs. The historical database and module library are summarized, and the cost and time corresponding to the module instances are shown in Table 1.

Table 1. Code and attribute of maintenance module and module instance of EMUs bogie.

Model Name		Instance Name	Module Instance Code	Cost (Ten Thousand Yuan)	Maintenance Time (h)	Module Attribute
Service modules	Installation and debugging service module	Site installation test	1	1.50	18.4	▲
		Remote installation test	2	0.80	22.6	
		Commissioned installation test	3	2.20	18.5	
	Consultation and training module	Basic train	1	0.56	8.6	▲
		Optimization train	2	1.20	17.2	
	Monitoring diagnostic module	Remote monitoring and diagnosis	1	4.58	2.4	△
		On-site monitoring and diagnosis	2	6.23	5.8	
	Spare parts supply module	Supply of original spare parts	1	5.45	4.5	▲
		Supply of non-original spare parts	2	3.55	5.0	
	Personalized service	Vehicle clean	1	0.12	4.55	△
		Vehicle beauty	2	0.25	5.6	
		Replace interior decoration	3	0.89	6.98	

Table 1. *Cont.*

	Model Name	Instance Name	Module Instance Code	Cost (Ten Thousand Yuan)	Maintenance Time (h)	Module Attribute
	Maintenance service module	Level 1 maintenance	1	8.70	5.2	▲
		Level II maintenance	2	15.60	5.4	
		Level III maintenance	3	18.90	5.1	
	Quality assurance module	Bogie warranty	1	5.20	7.6	△
	Emergency rescue service module	Multi-party joint request for help	1	8.60	9.5	▲
		Service providers ask for help independently	2	6.40	10.0	
Product modules	Axle box temperature sensor	Model HG-TSEN-01-S	1	0.0354	2.1	△
		Model DCGQT100B	2	0.0368	1.9	
	Axle box bearing	NSK	1	0.0450	2.04	△
		NTN	2	0.0420	1.83	
	Primary vertical shock absorber	KYB product	1	0.135	6.3	△
		Hitachi product	2	0.129	6.7	
	Air spring	KTS product	1	0.0150	0.8	△
		Tieke product	2	0.0185	0.75	
	Axle	Axle A	1	0.68	2.5	△
		Axle B	2	0.60	2.95	

In the above table, ▲ represents the mandatory module and △ represents the optional module. Select the module instances combination scheme from the above modules so the scheme has excellent performance, low cost, and short response time. At the same time, the maximum price C_{max} acceptable to customers is RMB700,000, the maximum waiting time T_{max} is 140 h, and the expected profit margin of the enterprise α is 22%.

Since the module combinations in the scheme are not all reasonable, specific configuration rules need to be followed. The configuration rules of this case are shown in Table 2. After the customer preferences are obtained, among them, 1 is the strongest preference, and 9 is the lightest preference. Analyze according to the prospect theory, the weights of technical characteristics are obtained, and then convert it into the weight of module instances through the correlation matrix between technical characteristics and module instances, and Table 3 is obtained.

Table 2. Configuration rules.

Number	Rule Types	Meaning
1	Mutually exclusive rule	KYB products are incompatible with Hitachi products, and choose one to install
2	Dependency rule	If the reducer type is KYB, NSK must be selected If you choose to seek help from multiple parties, you must decide to use the optimization train
3	Personalization rule	Parts that must be selected or not selected as specified by the customers

Table 3. Correlation description between module instances and technical characteristics.

Technical Characteristics	Energy Saving Performance	Timeliness	Adaptability	Reliability	Security	Availability	Specialty	Experience	Environmental Performance	Instance Weight
Preference	6	9	7	1	2	4	5	3	8	
Technical characteristics weight	0.0907	0.0369	0.074	0.2021	0.1645	0.1246	0.1074	0.1431	0.0566	0
Site installation test	3	3	3	9	9	3	3	5	1	0.037
Remote installation test	3	3	3	9	9	6	3	5	1	0.040
Commissioned installation test	3	3	3	9	9	8	3	5	1	0.042
Basic train	3	3	3	8	9	3	3	6	6	0.039

Table 3. *Cont.*

Technical Characteristics	Energy Saving Performance	Timeliness	Adaptability	Reliability	Security	Availability	Specialty	Experience	Environmental Performance	Instance Weight
Optimization train	3	3	9	6	6	1	9	9	3	0.040
Remote monitoring and diagnosis	1	1	1	6	1	9	1	1	6	0.023
On-site monitoring and diagnosis	1	1	1	9	3	9	3	1	6	0.031
Supply of original spare parts	3	3	3	9	9	9	6	1	1	0.041
Supply of non-original spare parts	3	3	3	8	9	9	3	6	3	0.043
Vehicle clean	3	3	1	9	9	9	1	8	1	0.043
Vehicle beauty	1	1	3	9	9	9	1	6	3	0.041
Replace interior decoration	1	1	3	9	9	9	3	9	3	0.046
Level 1 maintenance	8	9	3	3	1	1	3	3	3	0.022
Level II maintenance	8	9	1	1	1	1	1	1	3	0.014
Level III maintenance	9	3	1	1	1	1	1	1	1	0.013
Bogie warranty	1	3	3	9	6	9	9	3	1	0.040
Multi-party joint request for help	1	1	3	9	9	3	9	9	9	0.047
Service providers ask for help independently	3	3	3	6	8	3	8	8	3	0.040
Model HG-TSEN-01-S	3	3	1	3	3	3	9	9	3	0.030
Model DCGQT100B	3	1	1	3	3	3	9	9	3	0.030
NSK	1	3	3	9	9	9	3	3	3	0.040
NTN	1	3	9	8	3	9	3	3	3	0.035
KYB product	3	3	3	9	9	3	3	3	3	0.036
Hitachi product	3	3	3	6	9	3	3	3	3	0.032
KTS product	3	3	3	8	9	3	3	3	9	0.037
Tieke product	3	3	3	9	9	6	3	3	9	0.041
Axle A	1	3	1	9	9	3	9	3	3	0.038
Axle B	1	3	1	8	9	6	9	3	3	0.040

3.2. Solution Method

(1) **Encoded mode.** Adopt real coding, and the coding length is $M + N$, M represents the number of mandatory modules, and N represents the number of optional modules. The value range of the i-th real number in M code is $\left[1, C_{ij}\right]$, and the value range of the i-th value range is $\left[0, C_{ij}\right]$. C_{ij} represents the j-th instance in the i-th module, when $i \leq M$, it is a mandatory module, otherwise it is an optional module. A gene value of 0 means that the module does not participate in the scheme configuration, and a gene value of non-0 means the corresponding instance code of the module. The composition and values of the encoding scheme are shown in Figure 5.

$$[C_{1j} \quad C_{2j} \quad \cdots \quad C_{Mj} \mid \quad C_{(M+1)j} \quad \cdots \quad C_{(M+N)j}]$$

Figure 5. Encoded structure and value diagram.

(2) **Crossover and mutation method.** Crossover and mutation operations can significantly improve the search ability of the algorithm. This paper adopts real number coding, and due to the particularity of the coding method, this paper adopts one-point crossover and real value one-point mutation to generate offspring. The genes at any position of the two randomly selected parents are exchanged to obtain the offspring. The one-point crossover and mutation operation are shown in Figures 6 and 7. The mutation range of each module is the value range of the module.

*Parent*1 [1 5 4 3| 4 2 0 1]
*Parent*2 [2 3 1 2| 1 0 3 2]
↓
*Children*1 [1 3 4 3| 4 2 0 1]
*Children*2 [2 5 1 2| 1 0 3 2]

Figure 6. Schematic diagram of one-point crossover.

Parent [1 5 4 3| 4 2 0 1]
↓
Children [1 3 4 3| 4 2 0 1]

Figure 7. Schematic diagram of one-point mutation.

(3) **Algorithmic process.** Considering the multi-objective optimization problem, the traditional objective function linear weighting method and priority method cannot guarantee the optimality of the Pareto. Non-Dominated Sorting Genetic Algorithms (NSGA_II) adopts the elite retention strategy and has fast convergence speed and strong robustness. Therefore, this algorithm is used to solve the multi-objective problem in this paper. The algorithm-solving process is shown in Figure 8.

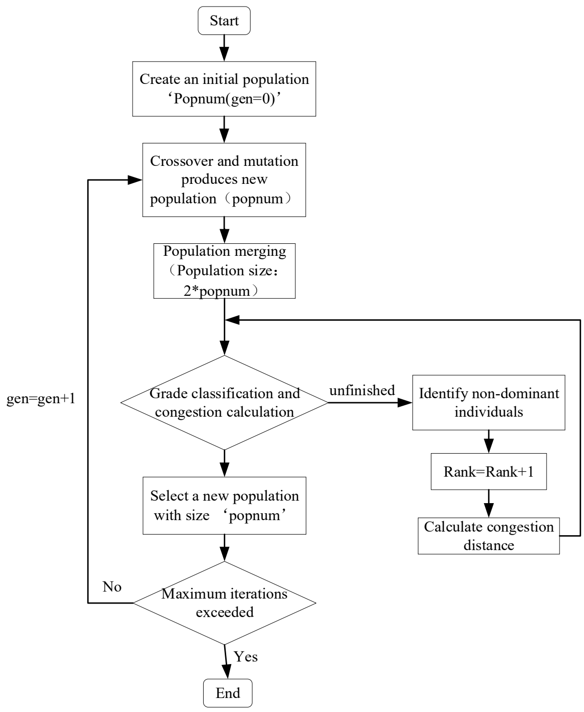

Figure 8. NSGA_ II algorithm flow chart.

(1) **Initializing parameters to generate the initial population.** Initializing various parameters and generating an initial population that meets the constraints of configuration rules according to the population size ‘popnum’.

(2) **Crossover and mutation.** Two parents were randomly selected for crossover and mutation operation to generate a new population with a size of ‘popnum’.

(3) **Grade separation and crowding distance calculation.** Merge the current population with the newly generated population to generate a population with population size ‘2*popnum’ and rank the population according to the objective function value. The higher the level is, the higher the individual fitness is. Then the crowding distance is used to measure the individual fitness value of the same non-dominated layer.

(4) **Generate current population.** Judge the three function values and directly change the individual level that does not meet the function value constraints to '*fnum* + 1'. Put the smaller level into the current population first, when the number of level '<*fnum*' is less than '*popnum*' and the number of level '*fnum* + 1' is greater than '*popnum*', sort according to the crowding degree, and find the ones with higher crowding degree into the current population until the number of the current population reaches '*popnum*'.

(5) **Cycle operation,** generation = generation + 1, until the end of the cycle.

4. Results and Discussion

Set the population size as 200, the crossover probability as 0.9, and the mutation probability as 0.1. After multiple runs, set the iteration times as 200. The initial solutions, Pareto solutions, and the evolution diagram of the objective function are solved with MATLAB as shown below, see Figures 9 and 10.

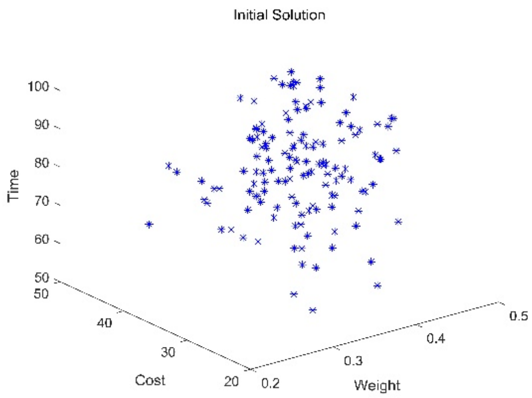

Figure 9. Initialization solutions.

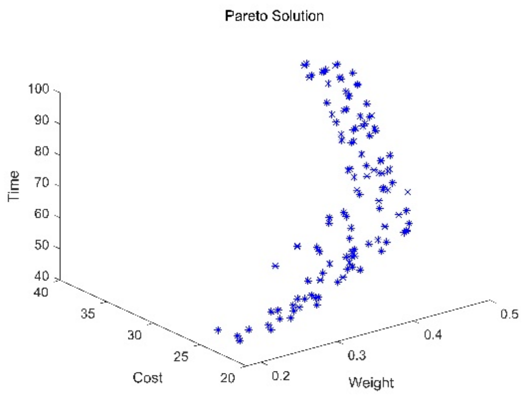

Figure 10. Pareto solutions.

It can be seen from the above figure that the initial solutions are messy. After calculation and optimization, the obtained three-dimensional graph has a particular law, that is, the Pareto front of the multi-objective function solutions. This shows the feasibility of this method in solving the optimization of service configuration.

The maximum value of the current population module instance weight after iteration is shown in Figure 11, and the evolution curves of the minimum cost and minimum time as the number of iterations increases are shown in Figures 12 and 13, respectively.

It can be seen from Figures 11–13 that the elitist strategy of the algorithm retains better solutions, making the solutions move in a better direction. According to the curve trend, the solutions of the next generation iteration are not inferior to that of the previous generation, and this method is effective. There are many schemes in the final set, and 15 schemes are selected as shown in Table 4:

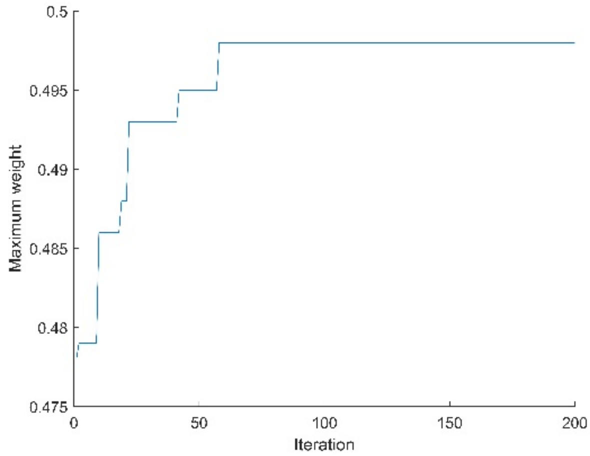

Figure 11. Evolution curve of maximum module instance weight.

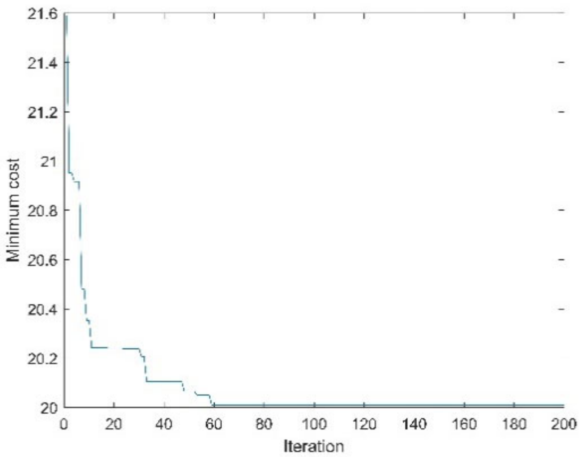

Figure 12. Minimum cost evolution curve.

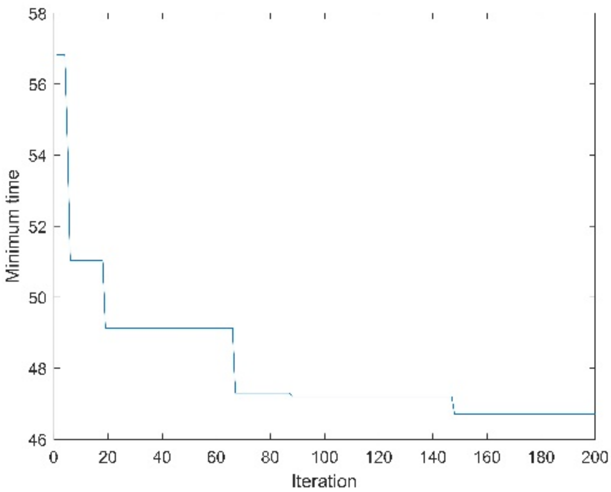

Figure 13. Minimum time evolution curve.

Table 4. Solution set of service configuration optimization scheme.

Number	Scheme Code	[Weight Cost Time]
1	[2 2 2 1 2 2 3 1 1 1 1 2 2]	[0.488 33.8039 94.52]
2	[2 1 2 1 2 0 0 0 0 0 0 1 0]	[0.227 20.025 52.2]
3	[1 1 1 1 2 0 0 0 0 0 0 2 0]	[0.224 22.6285 47.45]
4	[3 2 2 1 1 2 3 1 2 1 1 2 2]	[0.496 37.4053 89.72]
5	[1 1 1 1 2 0 0 0 0 0 0 1 0]	[0.221 22.625 47.5]
6	[3 2 1 1 1 2 3 1 2 1 1 2 1]	[0.49 39.3853 88.77]
7	[1 1 1 1 2 1 0 0 2 2 0 1 0]	[0.316 27.2838 53.63]
8	[2 2 2 1 1 0 1 1 2 1 1 2 1]	[0.457 29.0853 85.14]
9	[1 1 1 3 2 0 0 0 2 0 0 1 0]	[0.24 32.8618 49.3]
10	[2 2 2 1 1 2 3 1 2 1 1 2 1]	[0.491 36.0853 93.37]
11	[1 1 2 1 2 0 1 0 2 2 1 2 0]	[0.368 21.0623 62.53]
12	[1 1 2 1 2 0 0 0 0 2 0 1 2]	[0.3 21.367 52.78]
13	[2 2 2 1 1 0 1 0 1 1 1 2 1]	[0.419 23.8839 77.74]
14	[2 1 2 1 2 0 0 0 0 0 0 1 2]	[0.265 20.625 55.15]
15	[1 1 2 1 2 0 1 0 2 2 1 2 1]	[0.403 21.7423 65.03]

In the solution set provided in the above table, the first five are required modules, and the last eight are optional modules, which are arranged in the order of Table 1. For example, the configuration scheme represented by solution of No. 2: the second instance of mandatory module 1, the first instance of mandatory module 2, the second instance of mandatory module 3, the first instance of mandatory module 4, the second instance of mandatory module 5, and the first instance of optional module 7 are selected. The configuration scheme after the specific services: remote installation and commissioning, basic training, supply of non-original spare parts, level I maintenance, independent assistance of service providers, and KTS products are selected and configured. The weight of the module instance is 0.227, the cost is RMB200,250, and the response time is 52.2 h. It can be seen from the case that any scheme that can be selected by the customer is within its expected time and cost. Due to the modularization of maintenance service and the differentiation of service characteristics, the customer can more accurately express their needs in decision-making, avoiding the situation that the scheme selection cannot meet the expectations due to the lack of professional knowledge, and ensuring the profit margin of the enterprise. Customers can choose the final configuration scheme from a variety of optimization schemes according to their own needs for different preferences for different indicators, which realizes customer needs, reduces the enterprise and achieves a win–win situation.

5. Conclusions

In order to quickly respond to the customized maintenance needs of customers in many product and service combination schemes, the maintenance service configuration optimization is proposed. The service configuration optimization problem collects appropriate product and service module instances according to customer needs, and then solves the optimization scheme that meets customer needs. Therefore, the essence of the optimization problem of service configuration is to optimize product modules and service modules, maximize customer needs and enterprise interests, and provide necessary guarantee for achieving win–win.

The coexistence of large-scale and personalized of complex equipment maintenance has attracted more and more attention, and service-oriented manufacturing has promoted the transformation and development of the maintenance industry. In this paper, modular technology is used to manage modules, considering the constraints of scheme performance, cost, response time and module dependency, and mutual exclusion in the configuration process, a multi-objective optimization model is established and solved with Non-Dominated Sorting Genetic Algorithms (NSGA-II). Taking the maintenance service configuration of Electric Multiple Units (EMUs) bogie as an example, the selection and configuration of modules are carried out according to customer needs, and the maintenance service configuration is provided. Customers can choose the final configuration scheme from a variety of optimization schemes according to their own preferences for the scheme performance, time, and cost. The configuration optimization scheme maximizes the satisfaction of customer needs and enterprise interests to achieve a win–win result. In this paper, modularization technology is used to realize the large-scale management of maintenance service, and configuration technology is used to realize the personalized customization of customer service. However, the configuration rules are not discussed in depth. The future research work mainly focuses on the refinement of configuration rules, and in-depth analysis and research of multi-objective optimization.

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