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Multi-objective configuration optimization for product-extension service

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ABSTRACT

This study aims at optimizing the configuration of product-extension service (PES). PES is a new value-added paradigm which aids manufacturers to achieve sustainable growth and profitability. The configuration method is an efficient way for rapid PES customization to enhance customer satisfaction. However, the earlier service configuration approaches can produce a large number of feasible solutions, especially when there are more module instances, less constraints or fewer customers requirements. This will increase the burden of service solution screening and lower the efficiency of service delivery. To solve this problem, a multi-objective optimization model for configuration of the product-extension service is proposed. The optimization model simultaneously considers service performance, service cost and response time, and it is solved by non-dominated sorting genetic algorithm II (NSGA II) to obtain a set of optimal configuration solutions. Finally, an application of this service configuration optimization to elevator service demonstrates the potential of the method.
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1. Introduction

With the increasing competition and diversification of customer demand, low value-added manufacturing paradigms have been unable to meet the requirements of the market and environment. To achieve sustainable growth and profitability, many manufacturers transit from product manufacturers to providers of service [1]. They provide high-value product service solutions, such as product support, repair, maintenance, energy management, upgrading and recycling, etc. The service solutions are called product-extension services (PES), which can enhance the utility delivered by manufacturer to the users [2], and increase the product lifecycle [3]. Offering product-extension service (PES) also helps manufacturers to be differentiated from their competitors and to be made competitive [4–6]. The offered product-extension service must fulfill all customer requirements to ensure the expected performance of the product throughout the whole customer lifecycle [7,8].

However, the design and delivery of PES is often at lower efficiency, because there are more customer interactions, stakeholders' involvement, intangibility of service processes and service element heterogeneity in PES design. Many manufacturers provide unified after-sales service or off-the-shelf (OTF) service [9] for customers. This often does not really meet the needs of customers, because customers have different needs at different times. To respond to the market quickly and economically, most manufacturers have to rearrange the service resources or even redesign the service, which may lead to a waste of time and money. Service configuration is a good way to support manufacturers to enhance design efficiency and reduce design cost. It refers to selecting and combining pre-defined service modules to constitute integral service solutions in the light of given rules. The pre-defined modules are described by a series of attributes and connection rules [10,11]. However, the service configuration approaches may produce a large number of feasible solutions. The large configuration solution space will increase the burden of configuration screening. Although some service optimization models have been developed to find optimized solutions, they often focus on a single optimization objective (e.g. service cost) and ignore other aspects of PES (e.g. service performance and response time). This may lead to the configured PES having weakness in certain service attributes. However, the conventional configuration methods that focus on knowledge-based reasoning cannot manipulate a multiple objectives service configuration. Moreover, the traditional product configuration models are not suitable for PES configuration optimization due to PES's unique features (e.g. more stakeholders' involvement, service intangibility and service element heterogeneity). Besides, mutually inclusive/exclusive relationships are

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common among different service modules in the design of PES, because different stakeholders have different service processes and service resources. A new configuration optimization model needs to be developed to adapt to this change.

Therefore, in this paper, the PES characteristics and service module compatibility are considered in the process of configuration optimization modeling. An optimization model for PES configuration considering service performance, service cost, and service response time is developed. Non-dominated sorting genetic algorithm II (NSGA II) is used to solve the model to obtain the optimized PES solutions. In this way, the manufacturer is expected to flexibly meet customer requirements with a module-based PES at lower cost. The PES configuration optimization model is expected to enhance the customization ability of the service provider, because it can respond to customer requirements quickly by providing the customized PES. To our knowledge, there has been no such research in the past to help to build the configuration optimization model for product-extension service considering its characteristics.

The rest of this paper is organized as follows: Section 2 reviews the literature on service configuration; Section 3 describes the problem of PES configuration optimization. Section 4 presents the optimization methodology for the configuration of PES. Section 5 provides an industrial case study of the proposed optimization method. In this section, to reveal the superiority of the proposed PES configuration optimization method, the authors also compare it with the method in Gonzalez-Zugasti and Otto [12]. The last section concludes the present research.

2. Related work

Product configuration has received extensive attention in academia, because it is an effective way to achieve rapid design and a production environment for mass customization [13], but research on service configuration is still at an early stage.

2.1. Service configuration

Legnani et al. [14] presented a common representation framework for after-sales service processes based on a configuration model that connects typologies of assistance with product characteristics for service operations. To help manufacturers provide customer oriented solutions, Mannweiler and Aurich [15] also presented a configuration framework incorporating the necessary prerequisites and a systematic process. However, these service configuration frameworks are descriptive and don't provide specific implementation steps. Besides, they need to be further validated by applying them in different industries. To meet customer functional needs and perception needs, Long et al. [16] proposed a multiclass support vector machine model for configuration of product-extension service. Winter [17] proposed an open variant product model for financial services which was easy to represent configuration rules. Dausch and Hsu [18] developed a reference model for mass customizing service agreements. However, the reference model lacked some generalizability, and it was not designed for the configuration problem. Nanda et al. [33] proposed a service configuration mechanism using a graph-theoretical model derived from formal concept analysis. Cao et al. [32] developed an interactive service customization model. In this model, not only was the service content customizable, but also the service process could be constructed dynamically. Dong et al. [19] provided an ontology-based service product modeling approach for configuration. Meier and Massberg [20] developed a service configurator that considered the suppliers of manufacturer for the provision of customer-based services. Becker et al. [21] provided a configurative service engineering tool called Adapt(X) to generate customized organizational infrastructures, service processes and IT infrastructures. Research on configuration knowledge representation was also carried out. In order to gain higher effectiveness in configuration solutions, Shen and Wang [22] integrated the RULEX algorithm and local cluster neural network to extract configuration rules between service parameters and functional requirements, product characteristics or customer characteristics. Shen et al. [23] proposed an ontology-based approach to represent knowledge of product extension service configuration and developed a configuration system for product extension service. Heiskala et al. [24] used the unified modeling language (UML) to model knowledge that is important for configuring services.

However, most of those configuring tools were on the basis of descriptive procedures and not engineering methods. They were used to deduce all feasible service solutions in the light of certain rules, requirements and other constraints. However, this may produce a large number of feasible solutions when there are more module instances, less configuration constraints or fewer customer requirements. Besides, the conventional configuration methods which focus on knowledge-based or constraints-based reasoning cannot manipulate multiple objectives. Therefore, it is difficult to find the right service solutions for customers due to lack of a proper optimization model for PES configuration. Particularly, the PES always involves more service components and complex relationships, which also hinder the selecting of better configuration options.

2.2. Configuration optimization

To quickly obtain the right configured solutions, researchers developed some optimization methods. Fujita et al. [25] discussed product configuration under modular architecture and module communalization in a computational methodology. They proposed that product configurations could be considered as a problem of 0–1 integer programming, and developed a simulated annealing (SA) technique-based algorithm to solve it. Chakravarty and Balakrishnan [26] considered that the optimal set of module-options would only include the top ranked module-options in configuration. Xuanyuan et al. [27] presented a product configuration method based on multi-objective optimization, and they used a multi-objective genetic algorithm to solve the problem that converged to a Pareto optimal solution set from the large number of feasible solutions. Gonzalez-Zugasti and Otto [12] combined the objectives into a single objective function to configure an optimized product family.

However, most of the configuration optimization models are product-related, and they are not suitable for PES configuration optimization. This is because PES has different characteristics, such as more stakeholders' involvement, service intangibility and service element heterogeneity, etc. Thus, it is necessary to develop a new common model for PES configuration optimization. Besides, the earlier models of product configuration optimization were often solved by converting the problem of multi-objective optimization into a problem of single objective optimization, e.g. the method in Gonzalez-Zugasti and Otto [12]. This is not reasonable because the subjectivity in the conversion process may affect the accuracy of the configuration results. In addition, compatibility between the configured modules is often ignored, which may lead to the generation of unreasonable solutions.

3. Problem formulation of configuration optimization for PES

The objective of PES configuration is to find the right service portfolios based on different module instances that meet customer

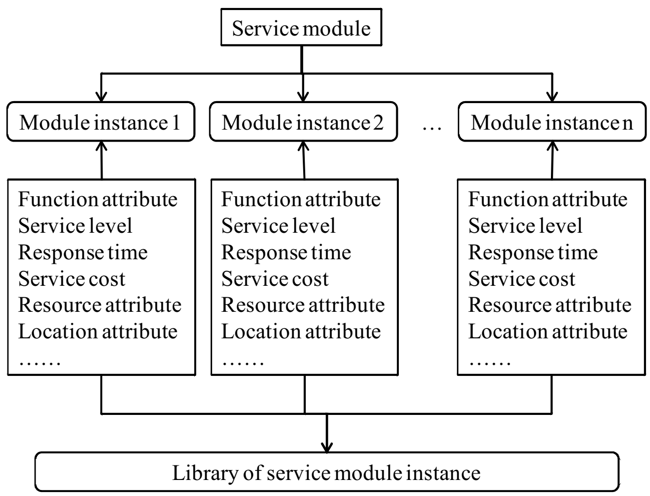


Fig. 1. Relationship between service module, module instance and module attribute.

requirements [23]. In this respect, the PES configuration can be considered as a process of service module instantiation driven by customer requirements. The modular configuration of PES helps service providers to achieve customized service deliveries and rapid responses to the market.

A service module is a kind of independent service unit with standard interfaces. The service module consists of different service components (e.g. service resources and processes) arranged in accordance with certain connection rules [34]. The service module also has attributes to portray itself, including service level, service response, and service time, etc. Therefore, these attributes can be used to identify and describe the service module. Different instances of the service module can be acquired by setting values for these attributes. For example, the service module of failure diagnosis has attributes as follows: response time, diagnosis mode, and feedback mode. By setting values for the three attributes, we can get different module instances, that is, a service module of remote failure diagnosis {response in half-hour, diagnosis with an intelligent system, online feedback} and a service module of on-site failure diagnosis {response in 1 h, diagnosis by experts, on-site feedback}. Fig. 1 shows the relationship between the service module and module instances and attributes. The service module can be classified into mandatory service module (function modules to achieve an essential service) and optional service module (additional module to meet special customer requirements). Modular PES configuration refers to the selection of proper service module instances to combine into integral PES solutions under certain constraints (see Fig. 2).

Hence, the problem of service configuration optimization can be regarded as the combinatorial optimization of service modules to maximize the fulfillment of customer requirements for product-extension service. In this respect, PES configuration can be seen as the process of searching for an optimal portfolio of module instance which satisfies pre-set constraints and targets. This is a typical problem of multi-objective combinatorial optimization. Proper service module instances are selected from the existing set of module instances according to the technical attributes derived from customer requirements. Combinatorial optimization of service module instances is then carried out to obtain different optimized service solutions satisfying diverse customer's needs.

4. Methodology for configuration optimization of PES

As shown in Fig. 3, in configuration of the product-extension service, the service design team elicits customer requirements of PES with certain tools, e.g. I-CAC analysis (industrial customer activity cycle analysis) [8], and they find the relationships between customer requirements and service attributes. Then, they establish mapping between technical attributes and service module instances. A modular service solution set can thus be obtained by retrieving appropriate module instances in accordance with certain rules and constraints.

The specific steps of service configuration optimization are described as follows:

First, some tools such as service QFD [28] are used to convert fuzzy customer requirements into service attributes. This is because most customers do not have the professional knowledge and experience of PES configuration. Therefore, they may not be able to effectively select the right service modules that meet their own needs. Customer requirement acquisition and conversion are not discussed in this paper because they are not the focus of the research.

Second, quantify the relationship between each service attribute and service module instance. Scores of 9,3,1,0 are used to indicate very strong, strong and weak and no relationship [29] between service attributes and service module instances. Therefore, service attributes that represent customer demand can be transformed into configuration requirements of the service module instance.

Finally, construct a configuration optimization model of PES considering service cost, service response time, and module compatibility constraints. The optimized service solution should have the best service performance, shortest response time and lowest service cost.

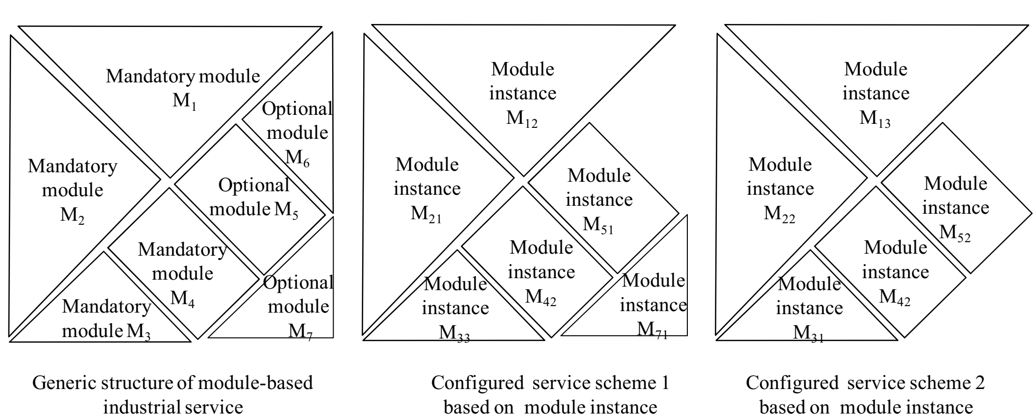


Fig. 2. Schematic view of configuration for product-extension service.

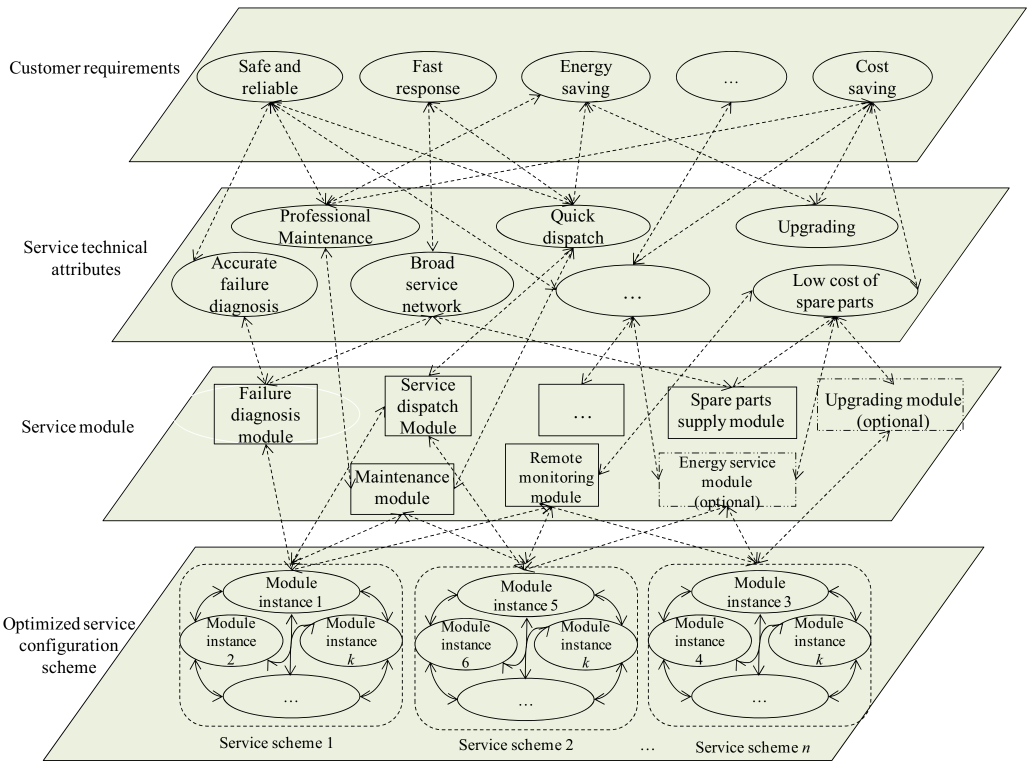


Fig. 3. Relationship between different levels of configuration for product-extension service.

4.1. Modeling for PES configuration optimization

4.1.1. Optimization objective of configured service performance

Assume the customer requirement vector is CR = [CR_1, CR_2, . . ., CR_n], where CR_i is the ith customer requirement (i = l, 2, . . ., n), n is the number of customer requirements. Assume the weight vector of customer requirement $W_{\mathrm{CR}} = \left[W_{\mathrm{CR}_1}, W_{\mathrm{CR}_2}, \ldots, W_{\mathrm{CR}_n}\right]$. The service attribute vector can be obtained as TA = [TA_1, TA_2, . . ., TA_P], the weight vector of the service attribute is denoted by W_{TA}, $W_{\mathrm{TA}} = \left[W_{\mathrm{TA}_1}, W_{\mathrm{TA}_2}, \ldots, W_{\mathrm{TA}_P}\right]$, where TA_l indicates the lth service attribute (l = l, 2, . . ., p), p is the number of service attributes. The weight determination for customer requirements and service attributes is not the focus of the paper, so it is not discussed here.

Assume there are totally M_1 mandatory service modules in the modular service scheme, and C_{1j} indicates the number of module instances in the jth mandatory module (j = l, 2, . . ., M_1), and M_{1jk} represents the kth instance of the jth module in the mandatory service module. Then, the total number of module instances in the mandatory module is $\sum_{j=1}^{M_1} C_{1j}$. Assume there are totally M_2 optional service modules in the modular service scheme, and C_{2j} indicates the number of module instances in the jth optional module (j = l, 2, . . ., M_2), and M_{2jk} represents the kth instance of the jth module in the optional service module. Then, the total number of module instances in the optional module is $\sum_{j=1}^{M_2} C_{2j}$.

Based on the analysis above, the problem of modular configuration of PES can be described as follows: select a module instance for each module in the M_1 mandatory service modules. After that, select N ($N \le M_2$) modules in the M_2 optional service modules, and then select an instance for each of the N modules. All the module instances that constitute the PES scheme can thus be obtained. Obviously, the total number of service module instances in PES scheme is $M_1 + N$.

Therefore, the configured service can be represented as follows:

$$S = \left\{ \left[I_{11}, I_{12}, \ldots, I_{1M_1}\right], \left[I_{21}, I_{22}, \ldots, I_{2N}\right] \right\}, \tag{1}$$

where S is the configured service scheme; I_{1k} is the kth instance of mandatory service module (k = 1,2, . . ., M_1); I_{2k} is the kth instance of optional service module (k = 1, 2, . . ., N).

The matrix of correlation between the service attributes and the service module instances can be represented as follows:

$$M_{I-\mathrm{TA}} = \begin{bmatrix} M_{1,I-\mathrm{TA}} \\ M_{2,I-\mathrm{TA}} \end{bmatrix}_{\left(\sum_{i=1}^{2}\sum_{j=1}^{M_i} C_{ij}\right)\times p}, \tag{2}$$

where $M_{1,I-\mathrm{TA}}$ is the matrix of correlation between the service attributes and the mandatory service module instances, and $M_{2,I-\mathrm{TA}}$ is the matrix of correlation between the service attributes and the optional service module instances. Both of them are respectively represented as follows:

$$M_{1,I-\mathrm{TA}} = \begin{bmatrix} \gamma_{1111} & \gamma_{1112} & \cdots & \gamma_{111p} \\ \gamma_{1121} & \gamma_{1122} & \cdots & \gamma_{112p} \\ \vdots & \vdots & \ddots & \vdots \\ \gamma_{11C_{11}1} & \gamma_{11C_{11}2} & \cdots & \gamma_{11C_{11}p} \\ \vdots & \vdots & \ddots & \vdots \\ \gamma_{1jC_{1j}1} & \gamma_{1jC_{1j}2} & \cdots & \gamma_{1jC_{1j}p} \\ \vdots & \vdots & \ddots & \vdots \\ \gamma_{1M_1C_{1M_1}1} & \gamma_{1M_1C_{1M_1}2} & \cdots & \gamma_{1M_1C_{1M_1}p} \end{bmatrix}_{\left(\sum_{j=1}^{M_1} C_{1j}\right)\times p}, \tag{3}$$

where $\gamma_{1jC_{1j}l}$ indicates the correlation between the lth service attribute and the C_{1j} th module instance of the jth module in the mandatory type of service module. $\gamma_{1jC_{1j}l}$ is judged by configuration engineers with rich experience and knowledge.

$$M_{2,I-\mathrm{TA}} = \begin{bmatrix} \gamma_{2111} & \gamma_{2112} & \cdots & \gamma_{211p} \\ \gamma_{2121} & \gamma_{2122} & \cdots & \gamma_{212p} \\ \vdots & \vdots & \ddots & \vdots \\ \gamma_{21C_{21}1} & \gamma_{21C_{21}2} & \cdots & \gamma_{21C_{21}p} \\ \vdots & \vdots & \ddots & \vdots \\ \gamma_{2jC_{2j}1} & \gamma_{2jC_{2j}2} & \cdots & \gamma_{2jC_{2j}p} \\ \vdots & \vdots & \ddots & \vdots \\ \gamma_{2M_2C_{2M_2}1} & \gamma_{2M_2C_{2M_2}2} & \cdots & \gamma_{2M_2C_{2M_2}p} \end{bmatrix}_{\left(\sum_{j=1}^{M_2} C_{2j}\right)\times p}, \tag{4}$$

where $\gamma_{2jC_{2j}l}$ indicates the correlation between the lth service attribute and the C_{2j} th module instance of the jth module in the optional type of service module. $\gamma_{2jC_{2j}l}$ is also judged by configuration engineers with rich experience and knowledge.

Taking into account the weights of service attributes, the correlations between the service module instances and the service attributes can be expressed as follows:

$$D = M_{I-\mathrm{TA}} \times W_{TA}$$
$$= \left(\sum_{l=1}^{p} \left(\gamma_{111l} w_{TA_l}\right), \sum_{l=1}^{p} \left(\gamma_{112l} w_{TA_l}\right), \ldots, \sum_{l=1}^{p} \left(\gamma_{ijkl} w_{TA_l}\right), \ldots, \sum_{l=1}^{p} \left(\gamma_{2M_2C_{2M_2}l} w_{TA_l}\right) \right), \tag{5}$$

where $\sum_{l=1}^{p} \left(\gamma_{ijkl} w_{TA_l}\right)$ indicates comprehensive correlation between the service module instance M_{ijk} and the vector of service attribute TA. It represents the ability of service module instance to meet the service attribute; W_{TA} is the weight vector of the service attributes.

ε_{ijk} is the binary decision variable that indicates the existence of service module instances in the process of optimizing service configuration. When $\varepsilon_{ijk} = 1$, the kth instance of the jth module in the ith type of services module (mandatory or optional) is selected; conversely, when $\varepsilon_{ijk} = 0$, the kth instance of the jth module in the ith type of services module (mandatory or optional) is not selected. Considering the correlation between the service module instance and the service attribute, and the existence of the service module instance in configuration, the optimization objective of comprehensive performance of the configured service can be expressed as

$$\max \mathrm{TAC} = \sum_{i=1}^{2}\sum_{j=1}^{M_i}\sum_{k=1}^{C_{ij}} \left[\varepsilon_{ijk} \sum_{l=1}^{p} \left(\gamma_{ijkl} w_{\mathrm{TA}_l}\right) \right]. \tag{6}$$

The comprehensive performance of the configured service TAC indicates the combination of the module instance's ability to meet the service attribute. The higher the value of TAC, the better the overall performance of the configured service.

4.1.2. Optimization objectives of service cost and response time

Construct the cost matrix of the product-extension service as follows:

$$\mathrm{Cost} = \left(\mathrm{Cost}_{111}, \mathrm{Cost}_{112}, \ldots, \mathrm{Cost}_{ijk}, \ldots, \mathrm{Cost}_{2M_2C_{2M_2}}\right), \tag{7}$$

where Cost_{ijk} indicates the service cost of the kth module instance of the jth module in the ith type of service module (mandatory or optional). Service cost is derived from the past service operation data. The total cost of the configured service Cost_s should be as small as possible. So the optimization objectives of the service cost can be obtained as follows:

$$\min \mathrm{Cost}_s = \sum_{i=1}^{2}\sum_{j=1}^{M_i}\sum_{k=1}^{C_{ij}} \left(\varepsilon_{ijk}\mathrm{Cost}_{ijk}\right). \tag{8}$$

Construct the response time matrix of the product-extension service as follows:

$$T = \left(T_{111}, T_{112}, \ldots, T_{ijk}, \ldots, T_{2M_2C_{2M_2}}\right), \tag{9}$$

where T_{ijk} indicates the service response time of the kth module instance of the jth module in the ith type of service module (mandatory or optional). The total response time of the configured service T_s should be as small as possible. So the optimization objectives of the service response time can be obtained as follows:

$$\min T_S = \sum_{i=1}^{2}\sum_{j=1}^{M_i}\sum_{k=1}^{C_{ij}} \left(\varepsilon_{ijk}T_{ijk}\right). \tag{10}$$

4.1.3. Constraints of service configuration optimization

Service configuration based on modules needs to satisfy the following constraints:

$$\sum_{j=1}^{M_1} \varepsilon_{1jk} = M_1, \quad \sum_{k=1}^{C_{ij}} \varepsilon_{ijk} = 1, \quad i = 1. \tag{11}$$

$$\sum_{j=1}^{M_2} \varepsilon_{2jk} \le M_2, \quad \sum_{k=1}^{C_{ij}} \varepsilon_{ijk} \le 1, \quad i = 2. \tag{12}$$

The front part of constraint (11) $\left(\sum_{j=1}^{M_1} \varepsilon_{1jk} = M_1\right)$ indicates that each of the M_1 mandatory service modules must be selected in the configuration process, and the latter part of constraint (11) $\left(\sum_{k=1}^{C_{ij}} \varepsilon_{ijk} = 1, \quad i = 1\right)$ reveals that only one module instance can be chosen for the selected mandatory service module. The front part of constraint (12) $\left(\sum_{j=1}^{M_2} \varepsilon_{2jk} \le M_2\right)$ indicates that all the M_2 optional service modules are not necessarily selected in the configuration process, and the latter part of constraint (12) $\left(\sum_{k=1}^{C_{ij}} \varepsilon_{ijk} \le 1, \quad i = 2\right)$ reveals that one instance can be selected at most for the optional service module.

Weight constraints of the service attributes can be expressed as follows:

$$\sum_{l=1}^{p} w_{\mathrm{TA}_l} = 1, \quad w_{\mathrm{TA}_l} > 0. \tag{13}$$

Although some service contracts may be agreed based on purely strategic reasons, accepting the possibility of a loss, the total cost of the configured PES in most cases is often expected to be less than the highest price that customer can afford. Then the customer may be willing to pay for the service, so the cost should satisfy the following constraint.

$$\mathrm{Cost}_S(1+\alpha) \le P_m, \tag{14}$$

where Cost_S is cost of the configured service; α is pre-set expected profit margin by service provider; P_m is the highest price of PES that the customers can afford.

In addition, the total response time of the configured PES must be less than the highest response time that a customer can endure. So the service response time should satisfy the following constraint:

$$T_S \le T_m, \tag{15}$$

where T_S is response time of the configured service; T_m is the highest response time that a customer can endure.

In addition, not all combinations of modules are rational in the service configuration process, and there may be a problem of mismatch. Therefore, the configuration of the PES module should also satisfy certain combination rules as follows.

(a) Mutually inclusive: if the service module instance M_{ijk} and service module instance $M_{i'j'k'}$ are mutually inclusive, and M_{ijk} is not selected, then $M_{i'j'k'}$ cannot be selected for configuration either, and vice versa.
(b) Mutually exclusive: if the service module instance M_{ijk} and service module instance $M_{i'j'k'}$ are mutually exclusive, then the configuration engineer can select M_{ijk} but cannot choose $M_{i'j'k'}$, and vice versa; that is, the configuration engineer can only choose one of the two module instances.

Configuration rules are mainly used to check the compatibility between modules in the configuration process. Define a variable $Q_{ijk-i'j'k'}$ as follows:

$$Q_{ijk-i'j'k'} = \begin{cases} 1 & M_{ijk} \text{ and } M_{i'j'k'}, \quad \text{mutually inclusive}, \\ -1 & M_{ijk} \text{ and } M_{i'j'k'}, \quad \text{mutually exclusive}, \\ 0 & \text{otherwise}, \end{cases} \tag{16}$$

where $i = 1, 2, j = 1, 2, \ldots, M_i, k = 1, 2, \ldots, C_{ij}$; $i' = 1, 2, j' = 1, 2, \ldots, M_i, k' = 1, 2, \ldots, C_{ij}'$. Then

$$\sum_{i'=1}^{2}\sum_{j'=1}^{M_i}\sum_{k'=1}^{C'_{ij}} Q_{ijk-i'j'k'}\varepsilon_{i'j'k'} = \begin{cases} 0 & \varepsilon_{ijk} = 0, \quad Q_{ijk-_{i'j'k'}} = 1. \\ 0 & \varepsilon_{ijk} = 1, \quad Q_{ijk-_{i'j'k'}} = -1. \end{cases} \tag{17}$$

In the light of the above constraint, if a module instance is not selected $\left(\varepsilon_{ijk} = 0\right)$, none of its mutually inclusive $\left(Q_{ijk-i'j'k'} = 1\right)$ module instances should be selected. If a module instance is selected $\left(\varepsilon_{ijk} = 1\right)$, its mutually exclusive $\left(Q_{ijk-i'j'k'} = -1\right)$ module instance cannot be selected. These constraints are the basis of penalties in the evolutionary algorithm.

4.1.4. Generic model of PES configuration optimization

Service configuration optimization is a problem of multi-objective combinatorial optimization under multiple constraints. So it can be expressed with the following general model:

$$\begin{aligned} & F(X) = (\text{TAC}(X), \text{Cost}_s(X), T_s(X)), \\ & \text{s.t.} \quad g_a(X) \ge 0, \quad a = 1, 2, \ldots, u, \\ & \quad h_b(X) = 0, \quad b = 1, 2, \ldots, v, \\ & \quad X = (\varepsilon_{111}, \varepsilon_{112}, \ldots, \varepsilon_{ijk}), \end{aligned} \tag{18}$$

where TAC(X) is the benefit-based objective function for the efficiency, the larger the better, and $\text{Cost}_s(X)$ and $T_s(X)$ are cost-based objective functions, the smaller the better. $g_a(X)$ and u are inequality constraints and the number of inequality constraints, respectively, $h_b(X)$ and v are equality constraints and the number of equality constraints, respectively, ε_{ijk} is 0–1 variable that indicates whether the service module instance is selected or not.

According to the description above, the proposed configuration optimization model for product-extension service can be expressed as follows:

$$\begin{cases} F(X) = \left\{ \max \displaystyle\sum_{i=1}^{2}\sum_{j=1}^{M_i}\sum_{k=1}^{C_{ij}} \left[\varepsilon_{ijk} \sum_{l=1}^{p} (\gamma_{ijkl} w_{\text{TA}_l}) \right], \min \sum_{i=1}^{2}\sum_{j=1}^{M_i}\sum_{k=1}^{C_{ij}} (\varepsilon_{ijk}\text{Cost}_{ijk}), \min \sum_{i=1}^{2}\sum_{j=1}^{M_i}\sum_{k=1}^{C_{ij}} (\varepsilon_{ijk}T_{ijk}) \right\}. \\ \qquad s.t. \quad \text{Cost}_S(1+\alpha) \le P_m, \quad T_S \le T_m; \\ \qquad \displaystyle\sum_{j=1}^{M_1} \varepsilon_{1jk} = M_1, \quad \sum_{j=1}^{M_2} \varepsilon_{2jk} \le M_2; \\ \qquad \displaystyle\sum_{k=1}^{C_{ij}} \varepsilon_{ijk} = 1, \quad i = 1; \qquad \sum_{k=1}^{C_{ij}} \varepsilon_{ijk} \le 1, \quad i = 2; \\ \displaystyle\sum_{l=1}^{p} w_{\text{TA}_l} = 1, \quad w_{\text{TA}_l} > 0; \\ \displaystyle\sum_{i'=1}^{2}\sum_{j'=1}^{M_i}\sum_{k'=1}^{C'_{ij}} Q_{ijk-i'j'k'}\varepsilon_{i'j'k'} = \begin{cases} 0 & \varepsilon_{ijk} = 0, \quad Q_{ijk-i'j'k'} = 1. \\ 0 & \varepsilon_{ijk} = 1, \quad Q_{ijk-i'j'k'} = -1. \end{cases} \end{cases} \tag{19}$$

4.2. Non-dominated sorting genetic algorithm II-based solution

Multi-objective GA appears to be suitable for PES configuration considering its nature of multi-objectives and combination. NSGA-II is the underlying algorithm for PES configuration, and it is derived from NSGA (non-dominated sorting genetic algorithm) that was developed by Deb et al. [30]. An overview of NSGA-II is described as follows.

NSGA can handle more complex and higher dimensional multi-objective problems. Srinivas and Deb [31] considered that it could find more Pareto frontiers and kept the diversity of the population in subsequent generations. However, NSGA has been criticized due to the requirement of assigning sharing parameter, complicacy of non-dominated sorting, and a lack of elitism [30]. NSGA-II is expected to overcome the above problems. To simplify the process of computation, NSGA-II adopts a fast non-dominated sorting method. Furthermore, the selection operator of NSGA is improved to build the mating pool through merging the populations of the parent and offspring and choosing the best population size solutions.

In this paper, NSGA-II is used to solve multi-objective optimization of PES configuration. For many problems of multi-objective optimization in the real world, there may be conflicts between optimization objectives. What we can obtain is a set of relative optimal solutions for different objectives, e.g. Pareto-optimal set. This is because no single optimal solution exists to satisfy all the objectives. Fig. 4 shows the algorithm process of NSGA-II.

Step 1: First, a random parent population (P_t) with size of N is created.

Step 2: Determine the non-dominant individuals, calculate the crowding distance for each individual and perform non-dominated sorting of the parent population and classify them into several fronts.

Step 3: Select individuals with binary tournament, and use operators of crossover and mutation to produce the offspring population O_t;

Step 4: Combine the parent population P_t and offspring population O_t to generate population H_t with size of $2N$;

Step 5: Perform fast non-dominated sorting for the population H_t, and calculate the stratified crowding distance. Select N individuals to form a new parent population P_{t+1};

Step 6: Determine whether the maximum allowable number of generation is reached;

Step 7: If it doesn't reach the maximum allowable number of generation, make $t = t + 1$, and repeat steps (3)–(6) until the maximum allowable number of generations is reached.

Step 8: The algorithm ends if the maximum allowable number of iterations is reached.

5. Case study: Configuration optimization for elevator service

5.1. Multi-objective configuration optimization of elevator service

Elevator Company M is a well known manufacturer who provides different types of elevators, including passenger/freight elevators, hospital elevators, escalators, and elevator monitoring systems, etc. The growth rate of profit and revenue of new elevators in Company M gradually decreased due to intense competition in the industry. In order to find a sustainable business model,

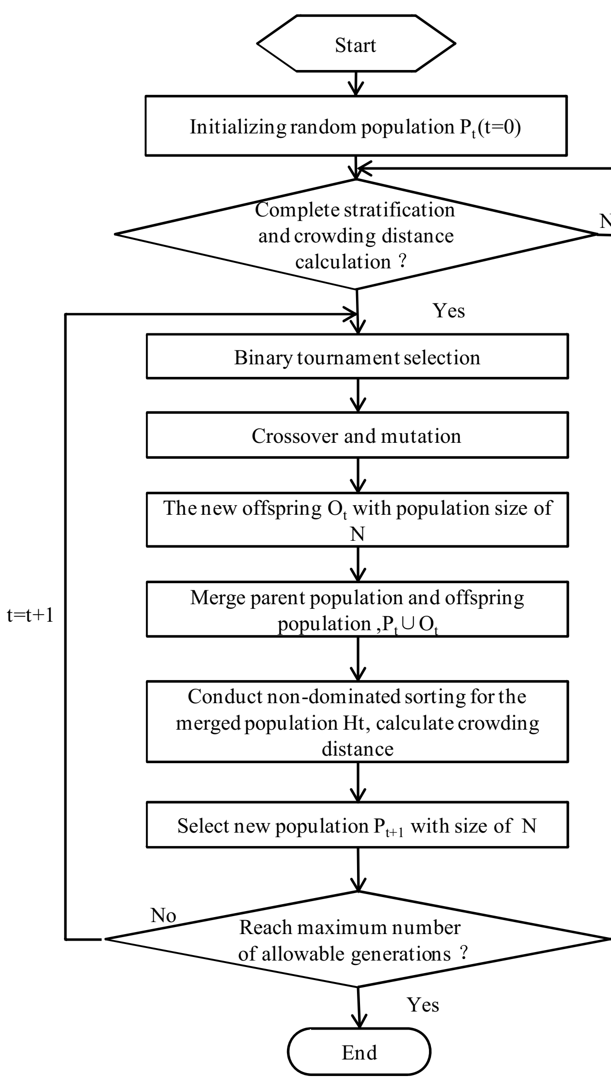


Fig. 4. Algorithm processes of configuration optimization model based on NSGA-II.

Table 1
Service modules and module instances of passenger elevator.

Service module name	Service module instance	Instance code	Cost	Response time	Module property
Knowledge support module of elevator service	Online knowledge support	M_{111}	1.25	0.3	▲
	Remote knowledge support	M_{112}	1.54	0.3	▲
	On-site knowledge training	M_{113}	2.55	1.5	▲
Consulting module for elevator purchase	Expert advisory	M_{121}	0.50	3.5	▲
	Self advisory with computer	M_{122}	0.30	0.2	▲
Module of installation and commissioning	Remote installation guidance	M_{131}	1.25	8	▲
	On-site installation guidance	M_{132}	0.62	16	▲
	Installation & commissioning	M_{133}	2.50	8	▲
Module of customer care	Regular telephone visit	M_{141}	1.55	0.5	▲
	Random visit	M_{142}	0.96	6.2	▲
	Visits based on complaints	M_{143}	1.24	5.5	▲
Repair service module	Maintenance with original spare parts	M_{151}	1.53	3.5	▲
	Maintenance with non-original spare parts	M_{152}	0.86	2.5	▲
Emergency repair module	Collaborative emergency repair	M_{161}	0.66	0.2	▲
	Independent emergency repair	M_{162}	1.50	0.3	▲
Module of spare parts supply	One-stop spare parts supply	M_{171}	2.43	2.2	▲
	Traditional spare parts supply	M_{172}	1.54	1.8	▲
Maintenance module	Maintenance/semimonthly	M_{181}	2.56	3	▲
	Maintenance/trimonthly	M_{182}	1.88	3	▲
	Maintenance/biannual	M_{183}	0.86	3	▲
Remote monitoring module	Basic condition monitoring	M_{191}	0.78	0.2	▲
	Operation monitoring	M_{192}	1.25	0.3	▲
Service planning module	Outsourced dispatching	M_{1101}	1.68	2.5	▲
	Dispatching of company M	M_{1102}	1.33	3.6	▲
Energy saving module (optional)	Energy-saving benefit sharing	M_{211}	3.58	8	△
	Energy management contract	M_{212}	5.16	8	△
Rehabilitation module (optional)	Decoration refurbishment	M_{221}	1.22	4	△
	...	...	...	...	...
	Elevator shaft upgrading	M_{224}	2.15	8	△
	Intellectualized upgrading	M_{225}	3.35	6	△
Module of life cycle data analysis(optional)	Life cycle alert of component	M_{231}	0.64	0.5	△
	Maintenance information inquiry and reporting	M_{232}	0.88	0.5	△

Note: Measuring unit of cost is ten thousand yuan, measuring unit of response time is hour; ▲ indicates mandatory service module, and △ indicate optional service module. Only part of data is listed here due to privacy restrictions and space limitation.

Company M decided to transform from a manufacturer to a service provider. It was expected to provide customized elevator services to ensure efficiency and effectiveness of elevator operation. In this way, Company M wants to enhance its competitiveness in the elevator service market. The company offers elevator service including installation, maintenance, repair, remote monitoring, elevator upgrading and spare parts supply, etc. The elevator service modules and module instances are shown in Table 1. The cost and response time of each service module instance in Table 1 are provided by the designers and managers in Company M. Only part of data is listed here due to privacy restrictions, but this doesn't affect the validation of the optimization method for the service configuration problem.

The goal of elevator service configuration optimization is searching for a proper module instance portfolio to achieve a relative optimum in overall service performance, service cost and response time. Considering the requirements of company M and the customer, the service configuration will also meet the following constraints:

- Company M's expected profit margin is 25%;
- The highest price of elevator service that a customer can afford is ¥300,000;
- The tolerable total response time for a customer is 50 h;
- Mutually inclusive and exclusive constraints are as follows: If the first instance of the repair service module (M_{151}) is selected, the second instance of the spare parts supply module (M_{172}) should not be selected. If the fifth instance of the refurbishment service module (M_{225}) is selected, the first instance of the energy saving module (M_{211}) should not be selected. If the first instance of the emergency repair module (M_{161}) is chosen, the first instance of the service planning module (M_{1101}) must be also selected. If the second instance of the emergency repair module (M_{162}) is chosen, the first instance of the remote monitoring module (M_{191}) must be also selected.

Elevator service attributes are as follows: reasonable recommendations of elevator selection (TA_1), fast and professional installation(TA_2), broad coverage of condition monitoring(TA_3), convenient and accurate failure diagnosis (TA_4), professional and timely maintenance(TA_5), elevator operation training (TA_6), repair service of high standard (TA_7), low cost of spare parts(TA_8), wide coverage of service network (TA_9), quick dispatching for maintenance and repair (TA_{10}), 7 d × 24 h emergency repair (TA_{11}), and elevator upgrading (TA_{12}). The matrix of correlations between service attributes and service module instances is shown in Table 3. The correlations are represented with scores of 0, 1, 3, and 9. A score of 0 indicates no relationship, while a score of 9 shows the strongest correlation between service attribute and service module instance. The weights of each service attribute are calculated with the method proposed in Song et al. [28], which is not the focus of this research. The weights of the service attributes are also shown in Table 2.

Parameters for the NSGA-II algorithm are set as follows: population size for elevator service configuration optimization is 300, crossover probability is 0.9, mutation probability is 0.1, and evolution generation is 300. The optimization results are shown in Figs. 5 and 6. As can be seen from Fig. 5, with the increasing generation of the algorithm iteration, the solution for elevator service configuration optimization mode gradually approaches the optimal solution. However, because the objectives of service performance, service costs and response time are not entirely consistent with each other, the final solution of the elevator service configuration is not a single point but a solution set. Therefore, a Pareto

Table 2
Matrix of correlations between elevator service attributes and service module instances.

Service attribute(TA_i)	TA_1	TA_2	TA_3	TA_4	TA_5	TA_6	TA_7	TA_8	TA_9	TA_{10}	TA_{11}	TA_{12}	$\sum \gamma_{ijkl} W_{TAl}$
Weight of TA_i (W_{TAi})	0.0815	0.0834	0.0852	0.0826	0.0867	0.0827	0.0823	0.0829	0.0826	0.0829	0.0834	0.0839	
M_{111}	3	3	3	9	1	3	3	3	3	3	9	3	3.8229
M_{112}	3	3	1	3	1	1	3	3	3	3	3	1	2.3233
M_{113}	9	9	1	9	3	3	9	1	1	1	1	3	4.1451
M_{121}	9	3	0	3	0	3	3	0	0	3	3	3	2.4771
M_{122}	3	1	0	1	0	3	1	0	0	1	3	1	1.1579
M_{131}	0	9	3	0	0	0	1	0	3	9	0	1	2.1663
M_{132}	0	3	1	0	0	0	1	0	1	1	0	3	0.8349
M_{133}	0	9	1	0	0	0	3	0	1	1	0	3	1.4999
M_{141}	3	0	0	3	3	0	3	0	3	3	1	0	1.5792
M_{142}	1	0	0	1	1	0	1	0	1	1	1	0	0.582
M_{143}	1	0	0	3	1	0	1	0	1	1	1	0	0.7472
M_{151}	0	0	3	1	3	0	9	3	1	1	9	3	2.7555
M_{152}	0	0	9	3	1	0	3	9	9	9	3	1	3.9179
M_{161}	0	0	9	9	0	0	1	1	9	3	9	0	3.4181
...	...	...	...	...	...	...	...	...	...	...	...	...	...
M_{221}	0	1	0	0	1	0	0	3	1	3	0	1	0.834
M_{222}	1	1	0	0	3	0	0	1	0	0	0	9	1.263
M_{223}	3	1	0	0	3	0	0	3	0	0	0	3	1.0884
M_{224}	3	1	0	0	3	0	0	3	0	0	0	3	1.0884
M_{225}	3	1	0	0	3	0	0	1	0	0	0	9	1.426
M_{231}	0	1	9	3	3	0	1	9	0	3	1	9	3.2737
M_{232}	0	1	3	1	9	0	1	3	0	0	3	3	2.0348

optimal solution set of the elevator service configuration can be obtained. The Pareto solution set in Fig. 5 has a reasonable distribution, because the NSGA-II algorithm uses a binary tournament selection strategy to maintain diversity of the population.

Each point in Fig. 5 represents an optimized elevator service configuration scheme. The average curves of service performance, service cost and response time in the process of 300 generations' evolution are respectively shown in Fig. 6. Apparently, after 30 generations' evolution, the averages of service performance, service cost and response time in each generation become stable, which indicates that the algorithm of optimization function has better convergence.

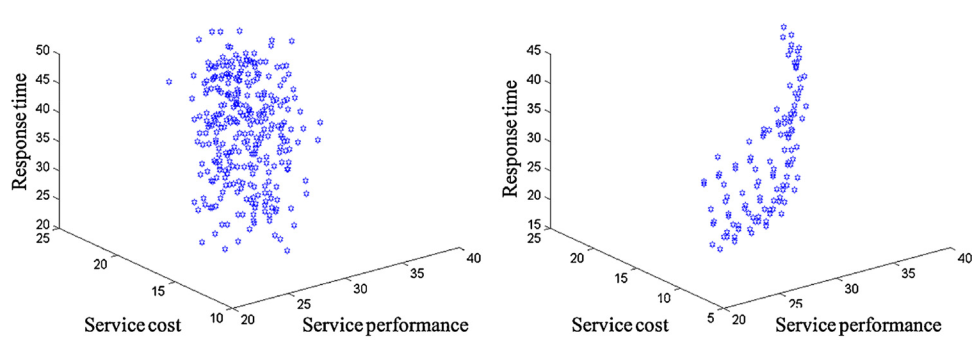
The service designers can then select an optimized configured service scheme for customers from the Pareto solution set. The optimization model of service configuration can help to make more informed choices for designers by providing customized product-extension service for different customers, and it enhances the efficiency of PES design due to its quickly finding the optimized configured service from many feasible solutions.

In this case study, five service schemes are selected in the light of customer preference for service performance, service cost and response time (see Table 3).

It can be seen from Table 3 that the five recommended elevator service schemes have their own pros and cons. For example, service scheme A1 has higher service performance (38.80) than that of service scheme A3 (35.39). However, the response time of A1 (40.7 h) is relatively slower to customer needs than A3 (31.1 h). Besides, service scheme A1 also has higher service cost (21.66) than that of service scheme A3 (17.32). Similar situations also exist among other configured service schemes. This is because the proposed PES configuration model simultaneously considers three objectives (e.g. service performance, service cost and response time), which are in conflict with each other. There is no single optimal PES solution but a set of valid optimal solutions exists. That is, the solution set of elevator service configuration is Pareto-optimal.

5.2. Sensitivity analysis

To analyze the influence of service attribute weights on the final optimal values (optimal performance, optimal cost, and optimal response time), a sensitivity analysis is made. The results of the sensitivity analysis are illustrated in Fig. 7. The results indicate that the optimal service performance is generally more sensitive to most of technical attribute weights than optimal service cost and optimal response time. Specifically, "7 d × 24 h emergency repair" (TA_{11}), "low cost of spare parts" (TA_8), and "convenient and accurate failure diagnosis" (TA_4) are the top three important factors affecting the optimal service performance (see Fig. 7a). The optimal service performance clearly increases as the three technical attribute weights become larger, while it is generally independent of the weights of TA_1 ("reasonable recommendations of elevator selection") and TA_{12} ("elevator upgrading"). The optimal service cost decreases with the



(a) Initial population (b) Pareto solution set

Fig. 5. Initial population and Pareto solution set of elevator service concepts.

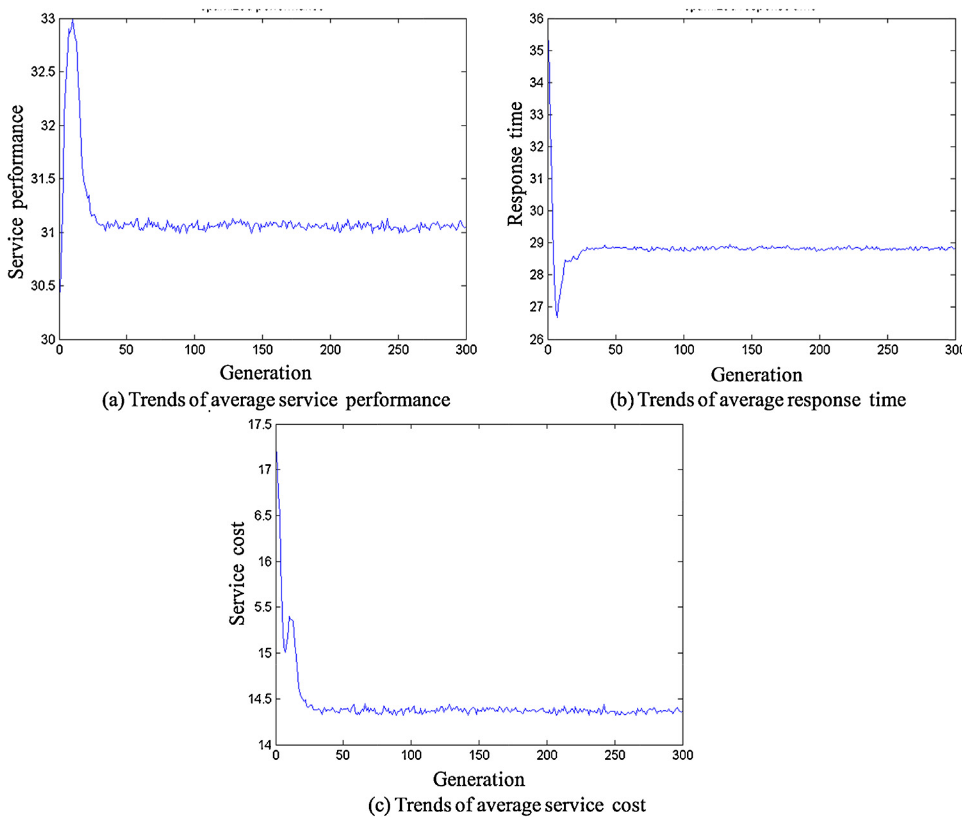


Fig. 6. The average trends of configuration optimizing objectives of elevator service.

Table 3
The five recommended elevator service schemes.

No.	Service module instance	Service performance	Service cost	Response time	Number of modules
A1	$M_{113}, M_{121}, M_{131}, M_{141}, M_{152}, M_{161}, M_{171}, M_{181}, M_{192}, M_{1101}, M_{211}, M_{224}, M_{231}$	38.80	21.66	40.7	13
A2	$M_{111}, M_{121}, M_{131}, M_{143}, M_{152}, M_{161}, M_{171}, M_{181}, M_{192}, M_{1101}, M_{211}, M_{221}, M_{231}$	37.39	19.12	40.5	13
A3	$M_{111}, M_{121}, M_{131}, M_{141}, M_{152}, M_{161}, M_{172}, M_{181}, M_{192}, M_{1101}, M_{211}, M_{231}$	35.39	17.32	31.1	12
A4	$M_{113}, M_{121}, M_{131}, M_{141}, M_{152}, M_{161}, M_{171}, M_{181}, M_{192}, M_{1101}, M_{211}, M_{222}, M_{231}$	38.97	21.94	38.7	13
A5	$M_{111}, M_{122}, M_{131}, M_{141}, M_{152}, M_{161}, M_{171}, M_{181}, M_{192}, M_{1101}, M_{212}, M_{231}$	36.56	19.59	28.2	12

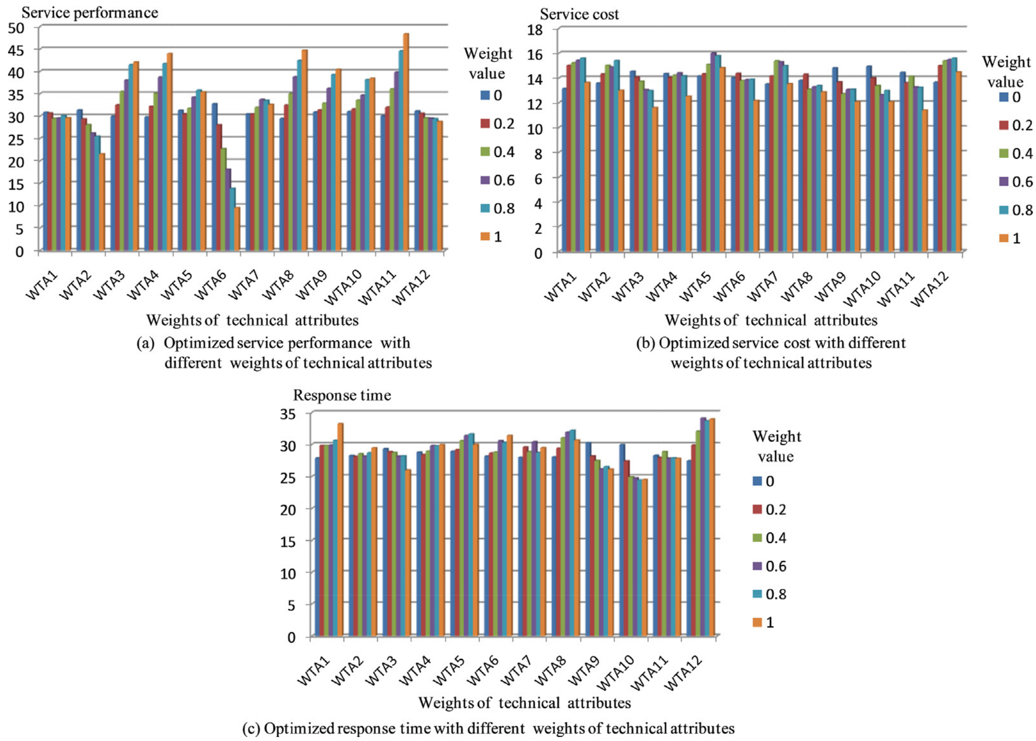
increase of the weights of TA_3 ("broad coverage of condition monitoring") (see Fig. 7b). It can be seen from Fig. 7c that TA_{10} ("quick dispatching for maintenance and repair") is an important factor for the optimal response time, because the optimal response time will gradually decrease when TA_{10} is given higher weights. The optimal response time is also generally independent of the weights of TA_2 ("fast and professional installation").

5.3. Comparison and discussion

To reveal the features of the proposed method for PES configuration optimization, comparisons are made between the proposed model and the method in Gonzalez-Zugasti and Otto [12]. Gonzalez-Zugasti and Otto [12] combined different objectives into a single objective function and solve the optimization model by GA. Different features of the two methods are summarized as follows:

First, the method used in Gonzalez-Zugasti and Otto [12] only produces one optimal solution each time, while the proposed optimization method can provide a set of optimal solutions for customer selection. For example, when the method in Gonzalez-Zugasti and Otto [12] is applied in the case study of elevator service, only one solution is produced, then the service module instance $M_{111}, M_{122}, M_{131}, M_{141}, M_{152}, M_{162}, M_{171}, M_{183}, M_{191}, M_{1101}, M_{211}$, M_{222}, and M_{231} are selected to configure into a elevator service scheme. The optimal service performance, the optimal service cost and the optimal response time of the configured service scheme are 33.20, 19.11 and 34.20, respectively. However, the proposed configuration optimization method provides various choices (a Pareto solution set) for customers, moreover, some optimal values are totally superior to that of the method in Gonzalez-Zugasti and Otto [12]. For example, The optimal service performance, the optimal service cost and the optimal response time of the elevator service scheme A_3 in Table 3 ($M_{111}, M_{121}, M_{131}, M_{141}, M_{152}, M_{161}, M_{172}, M_{181}, M_{192}, M_{1101}, M_{211}, M_{231}$) is 35.39, 17.32 and 31.10. The three optimal values are all superior to that of the method in Gonzalez-Zugasti and Otto [12]. This is because the method used in Gonzalez-Zugasti and Otto [12] converts the three objectives (service performance, service cost, and response time) into a single objective by assigning weights (0.33, 0.33, and 0.33) to them. The average trends of the optimal value of fitness function using the method in Gonzalez-Zugasti and Otto [12] is shown in Fig. 8. In contrast, the proposed configuration optimization method can simultaneously optimize different objective functions with the NSGA-II-based approach.

Second, the method in Gonzalez-Zugasti and Otto [12] and the proposed configuration optimization method for PES have different ways of solution searching. The entire population in the former approach only evolves to a peak of a non-inferior solution set, but



(a) Optimized service performance with different weights of technical attributes

(b) Optimized service cost with different weights of technical attributes

(c) Optimized response time with different weights of technical attributes

Fig. 7. Sensitivity analysis.

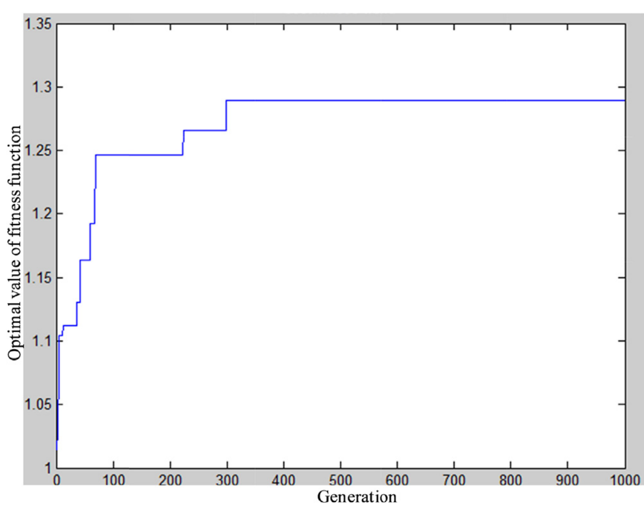
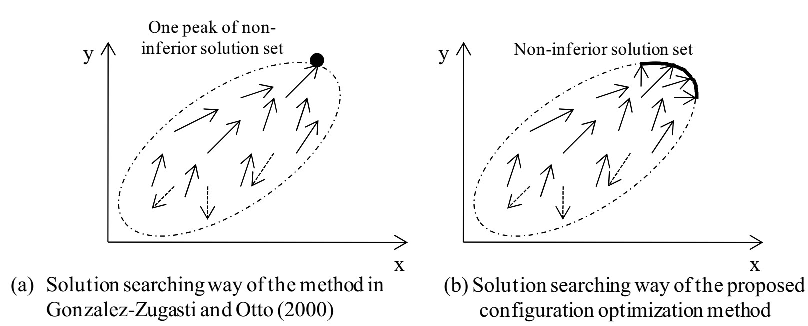


Fig. 8. The optimal value of fitness function with the method in Gonzalez-Zugasti and Otto [12].

the population in latter approach evolves to the non-inferior solution set (Pareto set). Thus, the method used in Gonzalez-Zugasti and Otto [12] can only get one solution for the multi-objective optimizing model. Fig. 9 shows the different ways of solution searching in the two methods. In fact, the conflicting objective functions cannot always achieve optimal values simultaneously. In this respect, the final solution of the multi-objective optimizing model is a Pareto set, but not a single solution. To obtain other possible optimal values, the method in Gonzalez-Zugasti and Otto [12] has to re-set the weights for the objective functions. For instance, when weights of objectives (service performance, service cost and response time) are given as 0.3, 0.1 and 0.6, respectively, the corresponding optimal values then transform into 30.19, 13.48, and 24.10. So the module instance M_{111}, M_{122}, M_{131}, M_{141}, M_{152}, M_{161}, M_{171}, M_{183}, M_{191}, M_{1101}, M_{221}, and M_{231} are selected to configure into an elevator service scheme.

Third, the method used in Gonzalez-Zugasti and Otto [12] belongs to the category of "decision before solving", while the configuration optimization method in this paper belongs to the category of "decision after solving". The former firstly uses some methods (e.g. weighted sum method) to convert the problem of



(a) Solution searching way of the method in Gonzalez-Zugasti and Otto (2000)

(b) Solution searching way of the proposed configuration optimization method

Fig. 9. Different ways of solution searching.

multi-objective optimization into a problem of single objective optimization, and then, it uses the genetic algorithm to solve the model to get one optimal solution. Although the method has lower computation load, it is difficult for decision makers to make tradeoffs between conflicting objective functions, because much information is required. However, the method in this paper firstly searches for the possible solution set that meets the requirements of different objective functions. Then, decision makers can select the solutions according to their actual situation.

In fact, the proposed multi-objective optimization model provides a tool to satisfy the customer's requirements under certain constraints (service cost, service response time, etc). This model considers both the manufacturing service provider's capability and customer's 'pain points' (e.g. response time and service price). The Pareto solution sets provide a wider choice for customers. Each Pareto solution represents a satisfactory service scheme. Differing with the traditional product, the product-extension service (e.g. repair and maintenance) is frequently required. Moreover, the customer has different requirements at different times due to the change of actual product operating conditions. Thus, a wider choice of service solutions is helpful for different customers, because customers can select the service solution from the Pareto solution sets according to their actual preferences.

6. Conclusions and suggestions

This paper proposes an optimization model for PES configuration. The model simultaneously takes service cost, service response time, and service performance as the optimization objectives. The multi-objective optimization model of service configuration is solved with the non-dominated sorting genetic algorithm II (NSGA II) to obtain the optimized service configuration set. The validation of the proposed model in elevator service configuration shows that it can be used as an effective method for PES configuration. To sum up, the proposed method reveals the following features:

The optimization model of service configuration can help designers to effectively and quickly find the optimized service solutions satisfying certain constraints from a large number of feasible solutions. In this respect, it enhances the efficiency of PES design.

Compared with the conventional configuration model with a single optimization objective, the proposed model comprehensively considers service performance, service cost and response time as optimization objectives, and it can provide a set of optimized service solutions that satisfactorily balance the multiple objectives of stakeholders.

The NSGA-II algorithm based solution avoids unnecessary subjectivity in the process of converting the multi-objective optimization model into a single objective optimization model.

The optimization model of PES configuration helps service providers to improve their capability to quickly deliver customized service at lower cost, which enhances customer satisfaction and customer value.

Although the proposed optimization method of PES configuration has some advantages, it provides a set of optimized service solutions, but not a single solution. Therefore, in future research, a service solution selection tool considering customer preference should be developed. The relationships between service attributes and service module instances are somewhat subjective, and they would be detected by more objective methods (e.g. Local Cluster Neutral Network) in future research.

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