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Optimal Remanufacturing Service Resource Allocation for Generalized Growth of Retired Mechanical Products: Maximizing Matching Efficiency

WANG Lei[#, 1], ZHAO Hui[#, 1], LIU Xiang[#, 1], Zhang Zelin[*, 1], XIA Xu-hui[*, 1], Steve Evans[2]

[1] Key Laboratory of Metallurgical Equipment and Control Technology (Wuhan University of Science and Technology), Ministry of Education, Wuhan 430081, China

[2] Centre for Industrial Sustainability, Institute for Manufacturing, University of Cambridge, Cambridge, UK

WANG Lei (candywang@wust.edu.cn), ZHAO Hui(zhaohui.wust@foxmail.com) and Xiang Liu (liuxiang@wust.edu.cn) contributes equally to this work.

Corresponding author: XIA Xu-hui (e-mail: xiaxuhui@wust.edu.cn), Zhang Zelin (e-mail: zhangzelin@wust.edu.cn).

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ABSTRACT Maximizing the residual value of retired products and reducing process consumption and resource waste are vital for Generalized Growth-oriented Remanufacturing Services (GGRMS). Under the GGRMS, the traditional product-oriented remanufacturing methods need to be changed: the products in GGRMS should be divided into multiple parts and different parts are treated in different ways to maximize residual value. However, this significantly increases the number of remanufacturing service activities and the complexity of the service activities network. Because a service activity may correspond to multiple service resources, the difficulty of service resources allocating significantly increase as the number of service activities under GGRMS increases. To improve the efficiency of resource matching, we proposed to first merge the redundant service activities in the service activity network, and then allocate the corresponding service resources. Therefore, we first used rough-fuzzy number and structural entropy weighting method to perform a coupling analysis on all service activities in the generalized growth scheme set and to merge redundant service activities. We then considered the interests of both the service providers and integrators and added flexible impact factors to establish a service resource optimization configuration model, and solved it with the Non-Dominated Sorting Genetic Algorithm (NSGA-Ⅱ). Finally, we, taking a retired manual gearbox as an experiment, optimized the service resource allocation for its generalized growth scheme set. The experimental results shown that the overall matching efficiency was increased by 74.56% after merging redundant service activities, showing that the proposed method is effective for the resource allocation of the generalized growth for complex single mechanical products, and can offer guidelines to the development of the RMS.

INDEX TERMS remanufacturing service; generalized growth; service activities coupling analysis; service resource allocation; allocation optimization

I. INTRODUCTION

Nowadays, a large amount of various machinery products in China have been starting to entered into the peak of retirement [1]. If these mechanical products cannot be used effectively after retirement, they will heavily harm environment and cause huge resource waste. Remanufacturing is an important support to reuse retired mechanical products and to develop circular economy [2][3]. Additionally, remanufacturing has rich theoretical and practical values [4][5][6]. However, as the importance of the services (e.g., design, procurement, marketing, logistics and decision-making) in the manufacturing value chain has gradually increased, traditional manufacturing industry has been transformed and entered into service-oriented manufacturing. Meantime, remanufacturing is an extension of manufacturing, and all links in the entire chain of remanufacturing have also embodied the idea of servicing, such as remanufacturing sales pricing service model [7], remanufacturing service system evaluation and decision-

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making [8], value-added service research in remanufacturing closed-loop supply chain [9], service warranty of scrap parts and optimal decision-making for remanufacturing [10]. Accordingly, we proposed the concept of Remanufacturing Service (RMS): Customer-oriented services of remanufacturing enterprise clusters with remanufacturing service integrators or integration platforms as the core. Based on remanufacturing services, provide services for the value-added activities of remanufacturing enterprises in the entire industrial chain [11]. Compared to traditional remanufacturing, the RMS not only integrates management and service systems, but also considers a full range of integrated technologies and services. It emphasizes the use of various technologies to virtualize physical service resources, and organizes and encapsulates them into integrated modules [12]. RMS is an integrated service method, which facilitates service providers to implement remanufacturing services according to service requirements. Recently, RMS-related research has achieved preliminary results, such as comprehensive benefits of remanufacturing services [13][14], selection of RMS knowledge resources [15], acquisition of remanufacturing service demand [16], and generalized growth decision of remanufacturing services [17].

Current research shows that RMS not only extends the value chain of retired products and maintains the intrinsic value of retired products, but also greatly improves the environmental, economic and social benefits [18]. However, complex mechanical products contain a large number of parts and components. In actual remanufacturing process, most of the retired parts and components are scrapped after disassemble, thereby hindering the full use of their residual value. Some parts are only remanufactured into original parts and finally assembled into original products. This kind of product-oriented remanufacturing method at the component level cannot create maximum value, and will still produce a certain amount of waste of resources. Therefore, we proposed the concept of Generalized Growth of Retired Machinery Products (GG_{rmp}) [17]. The concept points out that, for retired mechanical products and their parts with a certain residual added value, we should consider customers' demand information, combined with the Growth Factors (GF) such as failure mode, failure degree and structural complexity. Then, taking a series of remanufacturing Service Activities (SA) to realize the multi-level and multi-granularity growth process of the retired ones including from retired mechanical products to new products with improved performance or function or their retired parts are properly reused. The generalized growth process is shown in Figure 1.

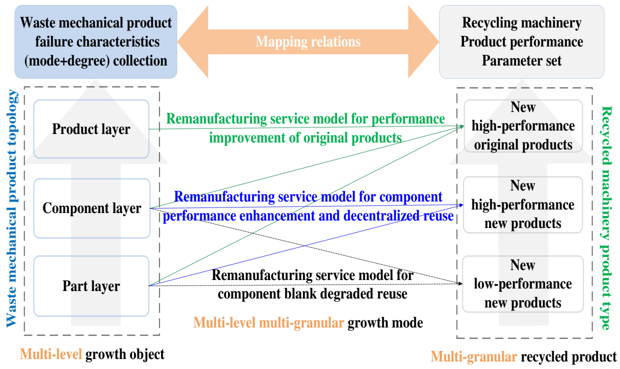

FIGURE 1. Generalized growth process of retired mechanical products

Among them, generalized recycled machinery products are mainly divided into three types: (1) New high-performance original products, which performance is restored to the same or even better than the original product through certain remanufacturing or repair methods; (2) New high-performance new products, which are obtained by remanufacturing or optimizing the combination of parts with remanufacturing value through certain remanufacturing technology; (3) New low-performance new products, whose parts cannot be restored to their original performance or whose remanufacturing value is insufficient for remanufacturing to degrade or reuse. The remanufacturing service scheme of each object is called Generalized Growth Scheme (GGS), the set of remanufacturing service schemes for these products, components and parts are called GGS_{set}, This type of remanufacturing service mode is called Generalized Growth-oriented Remanufacturing Service model ($GGRMS$), as shown in Figure 2. The parts after generalized growth can be sold directly or assembled with other new parts to produce new products, so as to give full play to the maximum residual value of retired mechanical products and form an open-loop remanufacturing service value chain. Taking a retired gearbox as an example, it can be remanufactured and restored to the original gearbox through certain procedures to improve its performance. If the remanufacturing value is not enough to be restored to the level of the original gearbox, some parts such as gears, intermediate shafts and housing can be assembled and remanufactured into new parts or products. Parts with low intrinsic value, such as keys, can be downgraded and remanufactured into another low-performance products or directly used as a blank. This service mode considers not only overall remanufacturing but also remanufacturing of parts and components, thereby maximizing the intrinsic value of retired mechanical products.

GGRMS mainly includes three types of users: service integrator, service demander and service provider [19]. Remanufacturing service integrator is the owner of the remanufacturing service integration platform. In the GGRMS service process, remanufacturing service integrator is responsible to formulate the GGS of each level object according to the customer's demand and the failure information of the retired mechanical products, as well as

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assist multiple service providers to carry out soft reorganization of service activities and integration of service resources.

Remanufacturing service integrators benefit from creating value for service demanders and service providers. Service providers offer remanufacturing services for specific needs, which can be divided into two types: 1) Remanufacturing providers, which include productive service activities such as evaluation, cleaning, testing, processing, and assembly of retired mechanical products, are the core of GGRMS; 2) Service resource providers are mainly responsible for providing relevant equipment, technical personnel and series of technical support, according to the GGS of the RMS integration platform, and under its supervision, as an outsourcing company to transfer service resources to remanufacturing providers. The service demander puts forward the demand and proactively proposes the service demand to the service integrator. Service providers can directly sell remanufactured products and generalized grown parts and components to market users, or directly accept retired mechanical products provided by market users. The remanufacturing service in GGRMS is a Service Resource Module (SRM) that virtualizes and encapsulates various resources, SRM contains the service resource elements involved in each service activities in the entire product life cycle [20], including machine tool equipment, operators, material resources.

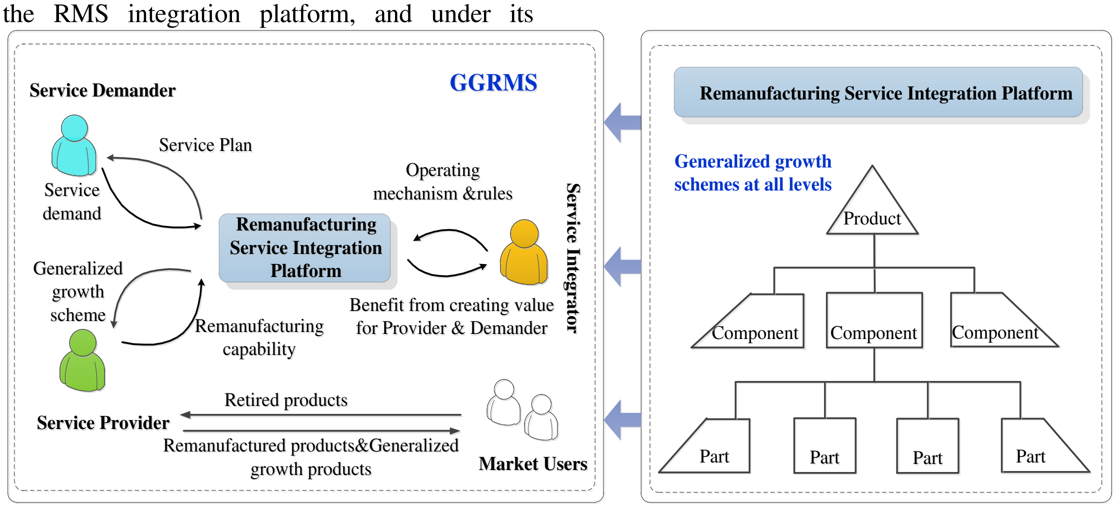

FIGURE 2. **Generalized growth-oriented remanufacturing service model**

Remanufacturing Service Resource Allocation (RMSRA) is the core part of implementing RMS, which can be defined as the process of service resource combination and optimization selection. In RMS, RMSRA aims to optimize service resources allocation. It considers the characteristics of extensive service resources and strong heterogeneity [21], and improves resource utilization efficiency from the perspective of overall service optimization [22][23]. However, in the GGRMS model, the complex retired mechanical product is dissembled into multiple parts, and each part determines the GGS according to GF. There may be crossover and redundancy of service activities between different GGSs, thereby increasing the difficulty of subsequent resource allocation. To improve the efficiency of service resources matching under the GGRMS mode, this paper considers coupling relevance of service activities, and merges redundant service activities between different GGSs before matching service resource.

To sum up, this paper proposed an RMSRA optimization method based on the GGRMS model, aiming to improve the matching efficiency of service resource and eventually maximizing the residual value of complex mechanical single products, and provided the guidelines for the resource allocation process under the RMS integrated platform. More specifically, this paper focuses on the following questions:

(1) How to improve the resources matching efficiency under the GGRMS mode?

(2) How to establish and solve the optimized RMSRA model under the GGRMS mode?

The rest of this paper is organized as follows. Section 2 reviews related work and briefly describes the problems and highlights of this paper. Section 3 analyzes the coupling relationship of service activities and builds a multi-objective RMSRA optimization model. Section 4 solves the model and Section 5 presents case studies. Section 6 presents future work and concludes the paper.

II. RELATED WORK

RMSRA embodies the choice of RMS, which is indispensable in the remanufacturing industry and is effective to reduce cost, improve efficiency, and protect the environment. The literatures related to resource allocation can be mainly categorized into two perspectives. The first is optimization model, including resource service selection and production decision based on TCQ (time, cost, quality) [24], web service composition optimization for large-scale perceived service quality [25], service-oriented logistics resource scheduling

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[26], classification-based integration services and composition [27]. These works often lacks the full mining of customer needs, affecting the quality of service. Regarding to this situation, Lin et al [28] proposed a resource constrained scheduling method based on genetic algorithm to meet user needs. However, it did not consider that customers may have subjective preferences in resource selection. Therefore, Wang et al [29] used the subjective trade-off method to solve the subjective preference problem in resource selection, and realized the coordinated optimization between the goals.

The second is algorithm. Xu et al [30] proposed an improved Pareto-based discrete bees algorithm to improve the performance of manufacturing service aggregation. Pashaki S et al [31] used cuckoo algorithm to solve the mathematical model based on group technology, which provided guidance for resource management of cloud environment. Zhou et al [32] used the evolutionary multi-objective optimization algorithm to determine the best candidate service combination and to provide insights for the SCOS problem. Other works used various optimization algorithms to study related problems under Quality of Service (QoS). For example, Lartigau J et al [33] proposed an improved artificial bee colony optimization algorithm based on QoS of service composition. Zhang et al. [34] proposed an improved particle swarm optimization algorithm for resource service selection based on QoS. Huang et al [35] proposed a chaos control optimization algorithm for service combination selection based on QoS.

In addition, the traditional remanufacturing resource allocation mainly focuses on the selection of equipment resources in the process link. Jun et al [36] established an equipment evaluation model with environmental and economic; Yi et al [37] established an equipment resource selection model with the shortest time and lowest cost. And improved the accuracy of remanufacturing and assembly of machine tool resources [38]; redesign of used parts-oriented mechanical equipment searched [39]; searched for equipment resources with the highest comprehensive benefit based on satisfaction degree and matching degree [40]; machine tool supply and demand matched based on quality demand and service capability mapping [41].

However, few works in the RMS field considered the GG_{rmp}. Even though some works have studied component-level remanufacturing and modular matching [42], these just related to certain characteristics in generalized growth, no group proposed GGRMS systematically. Compared with traditional remanufacturing, generalized growth increases the number of GGS, and each GGS is a combination of several service activities, thereby increasing the type and quantity of service activities. Because a service activity may correspond to multiple service resources, the difficulty of service resources matching significantly increase as the number of service activities under GGRMS increases. If we follow the traditional resource matching process, it will take a lot of time and the traversal efficiency will be low. For this reason, it is particularly necessary to reduce redundant service activities by analyzing the coupling between service activities. After eliminating redundant service activities, the overall resource allocating efficiency will inevitably be greatly improved. The service resources to complete the same service activities are fixed, just like laser cladding, the complete set of equipment required [43] consists of a laser, a cooling unit, a powder delivery device, and a processing workbench. The operator are specially trained people with certain work experience. Customer information and mobile resources required for sales and transportation are fixed resources. Therefore, the resources configured for high-coupling service activities are relatively fixed. Configuring resources without eliminating redundant service activities may cause repeated resources allocating, thereby wasting resources and greatly reducing the service efficiency. In addition, GGRMS has an additional service integrator compared to the traditional remanufacturing model, which is the core of the entire service system. Remanufacturing service integrators participate in the entire process of remanufacturing service resource allocation and monitor the service process. They need to bear the risks that may occur in the process of service resource allocation, and restrict service resource suppliers to ensure the smooth progress of resource allocation. Thus, to reduce the loss caused by uncertain resource factors, the flexibility of service resources needs to be considered. It guarantees the interests of both service integrators and service providers. The highlights of this paper are presented as follows:

(1) Explains the meaning of the GG_{rmp}, and puts forward the GGRMS model on this basis.

(2) Under the GGRMS model, the redundancy of service activities between different GGSs is considered, and redundant service activities are merged to improve the efficiency of SRM allocating.

(3) Different from the traditional remanufacturing resource allocation process, the flexible factor of resource allocation is added, which improves the interests of both the service integrators and the service providers under the GGRMS model.

III. COUPLING ANALYSIS AND RMSRA OPTIMIZATION MODELING

A. TRADITIONAL REMANUFACTURING AND GGRMS

The comparison between traditional remanufacturing and GGRMS of retired mechanical products is shown in Figure 3 (a) and (b).

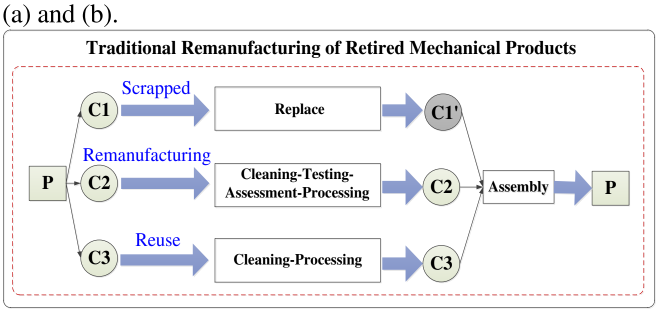

FIGURE 3. (a) Traditional remanufacturing of retired mechanical products

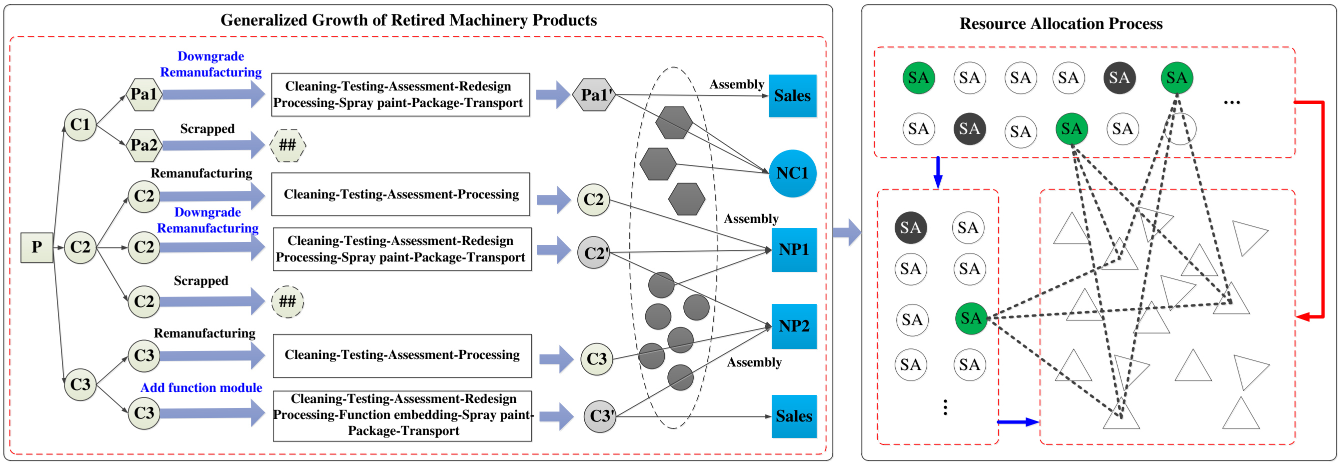

FIGURE 3. (b) Generalized growth of retired machinery product

In Figure 3(a), P is the product, $C1, C2, C3$ are components or parts, $C1'$ represents a new component or a new part. In Figure 3(b), $C1, C2, C3$ are components, $Pa1, Pa2$ are the parts after disassembly of $C1$, $Pa1'$ is a new part after $Pa1$ is downgraded and remanufactured, $C2'$ is a new component after $C2$ downgrade and remanufactured, $C3'$ is a new component generated by adding functional modules to $C3$, new parts and components are display in the dotted oval box, NP and NC represent new products and components formed by the assembly of generalized growth parts and other new parts. Obviously, the number and types of service activities under GGRMS will be more complex than traditional remanufacturing, and there will be many service activities that share resources, that is, redundant service activities. The red arrow represents the traditional remanufacturing resource allocating process; and the blue arrow represents the resource allocating process under GGRMS. Therefore, it is vital to search redundant service activities in the GGS_{set}.

B. GGS、SA AND SRM

In the case that a complex single product needs to be remanufactured, the remanufacturing service integrator divided the product into multiple parts and formulates a GGS for each object to form a GGS_{set}. Compared to traditional remanufacturing, it increases the number of remanufacturing schemes and enriches the granularity of remanufactured physical products. Then, each GGS is decomposed into multiple serial service activities to form service activities set (SA_{set}), such as detection, cleaning, and disassembly.

Suppose that $GGS_{set} = \{GGS_1, GGS_2, \ldots, GGS_m\}$, GGS_m is the generalized growth scheme of remanufacturing object m, $SA_{set} = \{SA_a^i, SA_a^j, SA_a^k \cdots, SA_a^l\}$, i, j, k, l are the number of service activities corresponding to the GGS, $i, j, k, l \in \mathrm{Z}, \mathrm{a} \in (1,2,3, \ldots, \mathrm{m})$. Then the relationship between GGS_{set} and SA_{set} can be denoted as follows:

$$\boldsymbol{GGS_{set}} = \begin{bmatrix} \boldsymbol{GGS_1} \\ \boldsymbol{GGS_2} \\ \boldsymbol{GGS_3} \\ \vdots \\ \boldsymbol{GGS_m} \end{bmatrix} \rightarrow \boldsymbol{SA_{set}} = \begin{bmatrix} \boldsymbol{SA_1^1} & \boldsymbol{SA_1^2} & \boldsymbol{SA_1^3} & \cdots & \boldsymbol{SA_1^i} \\ \boldsymbol{SA_2^1} & \boldsymbol{SA_2^2} & \boldsymbol{SA_2^3} & \ldots & \boldsymbol{SA_2^j} \\ \boldsymbol{SA_3^1} & \boldsymbol{SA_3^2} & \boldsymbol{SA_3^3} & \ldots & \boldsymbol{SA_3^k} \\ \vdots & \vdots & & \ddots & \\ \boldsymbol{SA_m^1} & \boldsymbol{SA_m^2} & \boldsymbol{SA_m^3} & \ldots & \boldsymbol{SA_m^l} \end{bmatrix} \quad (1)$$

The Service Resource Module (SRM) refers to the combination of all service resources involved in completing the service activities function in the process of satisfying the remanufacturing service of retired mechanical products, which include hardware resources and software resources: 1) hardware resources, which is directly related to the realization of service activities, such as transportation vehicles, cleaning equipment, machining/reprocessing equipment, shot peening equipment; 2) software resources, including human, financial, system module, knowledge, technical, capability, and computing resources. Each SA in the SA_{set} needs to match an SRM from the candidate resource modules screened by the RMS integration platform, so that the SA_{set} can obtain the best service effect. The process of optimal allocation of remanufacturing service resources as shown Figure 4.

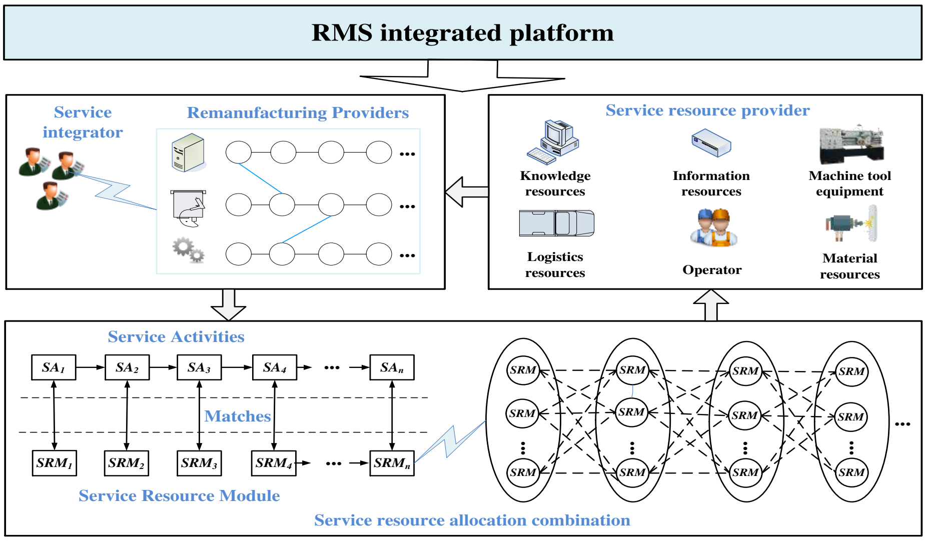

FIGURE 4. **Remanufacturing service resource optimization allocation process**

C. COUPLING ANALYSIS OF SERVICE ACTIVITIES

A complete and complex retired single product, its generalized growth-oriented remanufacturing service process can be described as: Service demand and the growth factors (input) of retired machinery products are under the guidance of the RMS integrated service platform (decision making) to supervise the process of remanufacturing providers performing service processes (process) to achieve expected service functions (output). There are many types of service activities being included in GGS_{set}. A GGS includes multiple service activities such as inspection and evaluation, disassembly, redesign, reprocessing, assembly, and reverse transportation. Reprocessing can be subdivided into multiple processing service activities according to the failure mode and performance of the remanufactured object. In different GGSs, service activities have a certain degree of coupling in the input hardware resources, software resources and human resources, meaning that there are a large number of same service resources among highly coupled service activities. Therefore, considering the similarity and sharing of resource requirements, we created the coupling evaluation index between service activities, which includes:

(1) **Hardware resources f_1:** Including materials, equipment, service sites and energy, further subdivided into equipment specifications, types and accuracy, material types and materials.

(2) **Human resources f_2:** Including technicians, developers and management personnel, further subdivided into operators' work types, technical capabilities, operating experience and knowledge reserves.

(3) **Software resources f_3:** Including service technology, knowledge, data, information and models. In the GGRMS process, two service activities may work based on the same network resource. They can be regarded as resource coupling. For example, failure detection and analysis of retired mechanical products share the same network resource: this means they are resource-coupled in the database of the RMS integrated platform.

Redundant service activities are determined by combining the coupling of the three services activities, and the highly-coupled service activities are combined into one service activity to reduce the complexity of the activities and the resource allocating time of SA_{set}.

1) INDEX QUANTIFICATION AND WEIGHT DIVISION

The coupling analysis of service activities involves a large number of input service resources and has two inherent uncertainties, namely, the ambiguity of linguistics and the subjectivity of interpersonal preferences. The ambiguity of linguistics is caused by the ambiguity of people's thinking and expressing preferences. The subjectivity of interpersonal preferences is due to the differences in judgements from people to people. Traditional analysis methods, such as *Analytic Hierarchy Process* (AHP), *Analytic Network Process* (ANP) and *Important Performance Analysis* (IPA), cannot take these two uncertainties into consideration. And *rough set theory* and *fuzzy set theory* have been widely adopted by various decision-making methods. Therefore, this section applies the *rough-fuzzy number* proposed by [44] to the evaluation of coupling between service activities. The goal is to utilize the ambiguity of linguistics and the subjectivity of interpersonal preferences simultaneously. The coupling of f_1, f_2 and f_3 can be calculated through the following process, respectively.

(1) *Step 1: Establish linguistics coupling matrix*, which invites a decision-making group composed of R-$EVEs$ (RMS evaluation experts, operation technicians) to evaluate the coupling of n service activities in SA_{set}. $EVEs$ use a set of linguistic variables to determine the strength of coupling (see Table 1).

TABLE 1. Fuzzy scale of linguistic variables

Linguistic variables	Clear number	Triangular fuzzy number （TFN）
Very strong (Vs)	1	（0.8，1，1）
Strong (S)	0.8	（0.5，0.8，1）
Middle (M)	0.5	（0.2，0.5，0.8）
Weak (W)	0.2	（0，0.2，0.5）
No (N)	0	（0，0，0.2）

The linguistic coupling matrix C_s^f which is made by the sth EVE is established as follows:

$$C_s^f=\begin{bmatrix}1 & C_{12}^{fs} & \cdots & C_{1n}^{fs}\\ C_{21}^{fs} & 1 & \cdots & C_{2n}^{fs}\\ \vdots & \vdots & \ddots & \vdots\\ C_{n1}^{fs} & C_{n2}^{fs} & \cdots & 1\end{bmatrix} \quad (2)$$

Where C_{ij}^{fs} denotes the strength of linguistic coupling between service activities SA_i and SA_j, and $C_{ij}^{fs}=C_{ji}^{fs}(i\neq j), s=1,2,\cdots,R$.

(2) *Step 2*：*Form fuzzy coupling matrix*. Following the fuzzy scale in Table 1, the element C_{ij}^{fs} of the linguistic coupling matrix C_s^f is converted to $\tilde{C}_{ij}^{fs}=(l_{ij}^s,m_{ij}^s,u_{ij}^s)$, where l_{ij}^s, m_{ij}^s and u_{ij}^s represent the low boundary, middle boundary and up boundary of the TFN, respectively. Then, the fuzzy coupling matrix $\tilde{C}_{ij}^{fs}$ can be represented as follows:

$$\tilde{C}_s^f=\begin{bmatrix}1 & \tilde{C}_{12}^{fs} & \cdots & \tilde{C}_{1n}^{fs}\\ \tilde{C}_{21}^{fs} & 1 & \cdots & \tilde{C}_{2n}^{fs}\\ \vdots & \vdots & \ddots & \vdots\\ \tilde{C}_{n1}^{fs} & \tilde{C}_{n2}^{fs} & \cdots & 1\end{bmatrix} \quad (3)$$

(3) *Step 3*：*Construct group fuzzy coupling matrix*, which sets the fuzzy coupling matrix constructed by $R\text{-}EVEs$ into a hypermatrix, and the group fuzzy coupling matrix $\hat{C}^f$ can be formulated as follows:

$$\hat{C}^f=\begin{bmatrix}1 & \hat{C}_{12}^{f} & \cdots & \hat{C}_{1n}^{f}\\ \hat{C}_{21}^{f} & 1 & \cdots & \hat{C}_{2n}^{f}\\ \vdots & \vdots & \ddots & \vdots\\ \hat{C}_{n1}^{f} & \hat{C}_{n2}^{f} & \cdots & 1\end{bmatrix} \quad (4)$$

And, $\hat{C}_{ij}^f=(\hat{l}_{ij},\hat{m}_{ij},\hat{u}_{ij}), \hat{l}_{ij}=\{l_{ij}^1,\dots,l_{ij}^s,\dots,l_{ij}^R\}, \hat{m}_{ij}=\{m_{ij}^1,\dots,m_{ij}^s,\dots,m_{ij}^R\}, \hat{u}_{ij}=\{u_{ij}^1,\dots,u_{ij}^s,\dots,u_{ij}^R\}$, group $TFNs$ can be denoted as $\hat{C}_{ij}^f=\{\tilde{C}_{ij}^{f1},\dots,\tilde{C}_{ij}^{fs},\dots,\tilde{C}_{ij}^{fR}\}$.

(4) *Step 4*：*Form rough-fuzzy coupling matrix*. According to the calculation in [44], the group fuzzy $TFNs$ $\hat{C}_{ij}^f$ can be transformed into a rough-fuzzy number. The calculation are shown as follows:

① Step 4.1：Get the upper and lower approximation of each TFN.

For the group $TFNs$ $\hat{C}_{ij}^f=\{\tilde{C}_{ij}^{f1},\dots,\tilde{C}_{ij}^{fs},\dots,\tilde{C}_{ij}^{fR}\}$, the upper and lower approximations of the sth TFN $\tilde{C}_{ij}^{fs}$ can be obtained by:

Upper approximation：

$$\overline{Appro}(\tilde{C}_{ij}^{fs})=\cup\{\tilde{C}_{ij}^{ft}\in\hat{C}_{ij}^f/\tilde{C}_{ij}^{ft}\geq\tilde{C}_{ij}^{fs}\} \quad (5)$$

Lower approximation：

$$\underline{Appro}(\tilde{C}_{ij}^{fs})=\cup\{\tilde{C}_{ij}^{ft}\in\hat{C}_{ij}^f/\tilde{C}_{ij}^{ft}\leq\tilde{C}_{ij}^{fs}\} \quad (6)$$

where $\overline{Appro}(\tilde{C}_{ij}^{fs})$ and $\underline{Appro}(\tilde{C}_{ij}^{fs})$ represent the upper and lower approximation of TFN $\tilde{a}_{ij}^s$, respectively.

② Step 4.2：Get the lower limit and upper limit of each TFN.

Therefore, the lower and upper limits of TFN $\tilde{C}_{ij}^{fs}$ can be defined as $\underline{Lim}(\tilde{C}_{ij}^{fs})$ and $\overline{Lim}(\tilde{C}_{ij}^{fs})$, which are mathematically represented by

$$\underline{Lim}(\tilde{C}_{ij}^{fs})=[\underline{Lim}(l_{ij}^s),\underline{Lim}(m_{ij}^s),\underline{Lim}(u_{ij}^s)]=\left[\frac{1}{N_s^L}\sum_{k=1}^{N_s^L}x_k^l,\frac{1}{N_s^L}\sum_{k=1}^{N_s^L}x_k^m,\frac{1}{N_s^L}\sum_{k=1}^{N_s^L}x_k^u\right] \quad (7)$$

$$\overline{Lim}(\tilde{C}_{ij}^{fs})=[\overline{Lim}(l_{ij}^s),\overline{Lim}(m_{ij}^s),\overline{Lim}(u_{ij}^s)]=\left[\frac{1}{N_s^U}\sum_{k=1}^{N_s^U}y_k^l,\frac{1}{N_s^U}\sum_{k=1}^{N_s^U}y_k^m,\frac{1}{N_s^U}\sum_{k=1}^{N_s^U}y_k^u\right] \quad (8)$$

where, x_k^l, x_k^m and x_k^u are respectively the elements of lower approximation for low boundary, middle boundary, and up boundary of TFN $\tilde{C}_{ij}^{fs}$. y_k^l, y_k^m and y_k^u are respectively the elements of upper approximation for low boundary, middle boundary, and up boundary of TFN $\tilde{C}_{ij}^{fs}$. N_s^L and N_s^U are the number of objects included in the lower approximation and upper approximation of TFN $\tilde{C}_{ij}^{fs}$.

③ Step 4.3：Convert each TFN to a rough-fuzzy form.

The rough-fuzzy form $RF(\tilde{C}_{ij}^{fs})$ of $\tilde{C}_{ij}^{fs}$ can be described as follows:

$$RF(\tilde{C}_{ij}^{fs})=[\tilde{C}_{ij}^{fsL},\tilde{C}_{ij}^{fsU}]=$$

$$[(l_{ij}^{sL},m_{ij}^{sL},u_{ij}^{sL}),(l_{ij}^{sU},m_{ij}^{sU},u_{ij}^{sU})] \quad (9)$$

$$[\tilde{C}_{ij}^{fsL},\tilde{C}_{ij}^{fsU}]=[\underline{Lim}(\tilde{C}_{ij}^{fs}),\overline{Lim}(\tilde{C}_{ij}^{fs})] \quad (10)$$

$$(l_{ij}^{sL},m_{ij}^{sL},u_{ij}^{sL})=[\underline{Lim}(l_{ij}^s),\underline{Lim}(m_{ij}^s),\underline{Lim}(u_{ij}^s)] \quad (11)$$

$$(l_{ij}^{sU},m_{ij}^{sU},u_{ij}^{sU})=[\overline{Lim}(l_{ij}^s),\overline{Lim}(m_{ij}^s),\overline{Lim}(u_{ij}^s)] \quad (12)$$

where, $\tilde{C}_{ij}^{fsL}$ and $\tilde{C}_{ij}^{fsU}$ are the lower and upper limit of the rough-fuzzy number $RF(\tilde{C}_{ij}^{fs})$. l_{ij}^{sL} and l_{ij}^{sU} are the lower and upper limits of the rough number $RN(l_{ij}^s)$. m_{ij}^{sL} and m_{ij}^{sU} are the lower and upper limits of the rough number

$RN(m_{ij}^{s})$. u_{ij}^{sL} and u_{ij}^{sU} are the lower and upper limits of the rough number $RN(u_{ij}^{s})$.

④ Step 4.4：Get the rough-fuzzy interval number of the group $TFNs$.

The rough-fuzzy interval number $RF(\hat{C}_{ij}^{f})$ of group $TFNs$ $\hat{C}_{ij}^{f}=\{\tilde{C}_{ij}^{f1},\dots,\tilde{C}_{ij}^{fs},\dots,\tilde{C}_{ij}^{fR}\}$ can be obtained by the following calculation principle:

$$RF(\hat{C}_{ij}^{f})=[C_{ij}^{fL},C_{ij}^{fU}] \tag{13}$$

$$C_{ij}^{fL}=(l_{ij}^{L},m_{ij}^{L},u_{ij}^{L})=\left(\frac{1}{R}\sum_{s=1}^{R}l_{ij}^{sL},\frac{1}{R}\sum_{s=1}^{R}m_{ij}^{sL},\frac{1}{R}\sum_{s=1}^{R}u_{ij}^{sL}\right) \tag{14}$$

$$C_{ij}^{fU}=(l_{ij}^{U},m_{ij}^{U},u_{ij}^{U})=\left(\frac{1}{R}\sum_{s=1}^{R}l_{ij}^{sU},\frac{1}{R}\sum_{s=1}^{R}m_{ij}^{sU},\frac{1}{R}\sum_{s=1}^{R}u_{ij}^{sU}\right) \tag{15}$$

where, C_{ij}^{fL} and C_{ij}^{fU} are the lower and upper limits of the rough-fuzzy interval number $RF(\hat{C}_{ij}^{f})$. l_{ij}^{L} and l_{ij}^{U} are the upper and lower limits of the rough interval $RN(\hat{l}_{ij})$. m_{ij}^{L} and m_{ij}^{U} are the upper and lower limits of the rough interval $RN(\hat{m}_{ij})$. u_{ij}^{L} and u_{ij}^{U} are the upper and lower limits of the rough interval $RN(\hat{u}_{ij})$.

⑤ Step 4.5：Get the rough-fuzzy coupling matrix.

After summarizing the group $TFNs$ $\hat{C}_{ij}^{f}$ into the rough-fuzzy number $RF(\hat{C}_{ij}^{f})$, the group fuzzy coupling matrix $\hat{C}^{f}$ can be converted into the rough-fuzzy coupling matrix $RF(\hat{C}^{f})$.

$$RF(\hat{C}^{f})=\begin{bmatrix}1 & RF(\hat{C}_{12}^{f}) & \cdots & RF(\hat{C}_{1n}^{f})\\ RF(\hat{C}_{21}^{f}) & 1 & \cdots & RF(\hat{C}_{2n}^{f})\\ \vdots & \vdots & \ddots & \vdots\\ RF(\hat{C}_{n1}^{f}) & RF(\hat{C}_{n2}^{f}) & \cdots & 1\end{bmatrix} \tag{16}$$

(5) *Step 5*：*Get the weight of the coupling index.*

In order to avoid mutation value leading to the distortion of the coupling evaluation results and reduce the uncertainty of the weight assignment, we adopted *structural entropy* [45] to calculate the weights of coupling judgment indicators for remanufacturing service activities. The detailed steps are given as follows:

Let R-$EVEs$ sort the coupling judgment indicators.

Construct coupling judgment indicators set for remanufacturing service activities:

$$\boldsymbol{F}=\{F_1,F_2,\dots,F_f\} \tag{17}$$

where F_j is the jth coupling judgment index. In this paper, we set $f=3$.

Collect the opinions of R-$EVEs$ to construct a priority matrix of remanufacturing coupling judgment indicators:

$$\mathbf{A}=[a_{ij}]_{R\times f} \tag{18}$$

where a_{ij} is the priority ranking of the ith EVE on the jth coupling judgment index, and the value is $\{1,2,3\}$.

The membership matrix of a_{ij} is $\boldsymbol{B_1}$, and the calculation method is:

$$\mathrm{b}_{ij}=-\ln(m-a_{ij})/\ln(m-1) \tag{19}$$

where m is the amount of conversion parameters, which is related to the maximum priority sequence number f. According to [46], let $m=f+2$, then m=3+2=5.The average recognition matrix of R-$EVEs$ to F_j in Equation (17) is $\boldsymbol{B_2}$, and the calculation method is as follows:

$$b_j=(b_{1j}+b_{2j}+\cdots b_{Rj})/R \tag{20}$$

Then the blindness of the coupling judgment index for remanufacturing service activities is:

$$Blind_j=\left|\left\{\begin{matrix}[\max(b_{1j}+b_{2j}+\cdots b_{Rj})-b_j]+\\ [\min(b_{1j}+b_{2j}+\cdots b_{Rj})-b_j]\end{matrix}\right\}/2\right| \tag{21}$$

Obtain the overall awareness value of R-$EVEs$ on the coupling judgment index F_j of remanufacturing service activities:

$$Aw_j=b_j(1-Blind_j);\ Aw_j>0 \tag{22}$$

Obtain the evaluation vector of the coupling judgment index $\boldsymbol{F}$ of all remanufacturing service activities by R-$EVEs$:

$$\boldsymbol{Aw}=[Aw_1,Aw_2,Aw_3] \tag{23}$$

Normalize Equation (23) to have the weight of the jth index:

$$\delta_j=Aw_j/\sum_{f=1}^{3}Aw_j \tag{24}$$

Then the weight vector of the remanufacturing service activity coupling judgment index set is as follows:

$$w_f=[w_{f1},w_{f2},w_{f3}] \tag{25}$$

2) COMPREHENSIVE COUPLING DETERMINATION

Comprehensive coupling degree is a comprehensive measurement of the coupling of hardware resources, human resources and software resources between SA_i and SA_j. And the rough-fuzzy comprehensive coupling strength $RF(\hat{C}_{ij})$ can be expressed as:

$$RF(\hat{C}_{ij})=w_{f1}RF(\hat{C}^{f1})+w_{f2}RF(\hat{C}^{f2})+w_{f3}RF(\hat{C}^{f3}) \tag{26}$$

where the coupling index weight satisfies the following conditions:

$$w_{f1}+w_{f2}+w_{f3}=1 \tag{27}$$

$RF(\hat{C}^{f1}),RF(\hat{C}^{f2}),RF(\hat{C}^{f3})$ represent the rough-fuzzy coupling matrix of the coupling indicators of hardware resources, human resources, and software resources, respectively. They use Equations (2) - (16) to calculate.

Obtain a clear comprehensive coupling matrix: in order to merge redundant service activities, the comprehensive coupling strength $RF(\hat{C}_{ij})$ needs to be transformed into a concise form. The clear comprehensive coupling strength C_{ij} can be obtained as follows:

$$C_{ij} = \frac{(C_{ij}^{lL}+4C_{ij}^{mL}+C_{ij}^{uL}+C_{ij}^{lU}+4C_{ij}^{mU}+C_{ij}^{uU})}{12} \quad (28)$$

where, C_{ij}^{lL}, C_{ij}^{mL} and C_{ij}^{uL} respectively represent the low boundary, middle boundary and up boundary of the lower limit of $RF(\hat{C}_{ij})$. C_{ij}^{lU}, C_{ij}^{mU} and C_{ij}^{uU} respectively represent the low boundary, middle boundary and up boundary of the upper limit of $RF(\hat{C}_{ij})$.

D. HIGHLY COUPLED SA MERGER

The judgment threshold of redundant service activities is set as $\boldsymbol{\theta}$, and the service activities whose comprehensive coupling clear number exceeds the threshold are combined, see Figure 5.

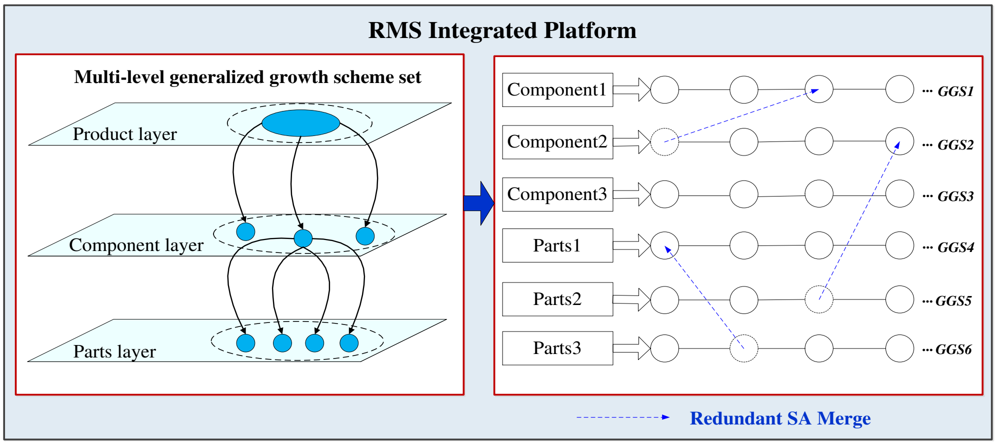

FIGURE 5. **Service activity coupling and merging**

Figure 5 shows the SA_{set} in the multi-level GGS_{set}, the parts with the same color represent service activities with a comprehensive coupling clear number exceeding θ. In order to simplify the problem complexity and intuitively show the allocating efficiency, we made two assumptions:

(1) Each SA consumes the same time to configure service resources on the RMS integrated platform. Let TN_{SA} be the total number of all service activities in GGS_{set}, and NC_{SA} the number of redundant service activities. Then the overall allocating rate improved by the GGS_{set} can be denoted by:

$$\mathrm{E}_m = \mathrm{NC}_{SA}/\mathrm{TN}_{SA} \quad (29)$$

(2) Let the set of coupling types of service activities be $Type = \{Type_1, Type_2, \cdots, Type_r\}$, N_{Type}^i represents the number of coupled service activities in each type, $i \in \{1,2,\cdots,\mathrm{r}\}$, and

$$\sum_{i=1}^{r} N_{Type}^i = \mathrm{NC}_{SA} + \mathrm{r} \quad (30)$$

Then the improved allocating rate of each type of coupled service activity can be denoted as:

$$\mathrm{E}_{Ri} = \frac{N_{Type}^i - 1}{N_{Type}^i} \quad (31)$$

E. RMSRA OPTIMIZATION MODEL

During the traditional remanufacturing resource allocation process, remanufacturing providers only pay attention to service quality factors such as time $\boldsymbol{T}$ (logistics time between adjacent SA, processing time, waiting time), cost $\boldsymbol{C}$ (logistics cost, processing cost, connection cost between adjacent SA) and quality $\boldsymbol{Q}$ (remanufacturing quality qualification rate) required for service resources, and often neglect other flexible factors. The flexibility of service resource combination refers to the ability of remanufacturing service resource combination to still complete service activities when there are many uncertain factors that affect the dynamic combination of remanufacturing service resources. These uncertain factors include: 1) As the remanufacturing providers progresses, service activities may change or need to be modified; 2) After the optimization of the allocation, a certain resource supplier in the service resource combination may exit and malfunction. This will be related to the reliability and success rate of the service resource combination, and it will easily lead to the inability to complete SA_{set} efficiently, which greatly affects all parties. Therefore, in order to provide best service for remanufacturing providers and to ensure the healthy development of RMS integration platform, remanufacturing service integrators need to pay more attention to service flexibility factors such as reputation, reliability (resource reliability and technical reliability) and service level (service ability and service evaluation) of service resource providers. Learn from [47][48], the evaluation index system for constructing the RMSRA optimization model is shown in Figure 6.

There are often multiple $SRMs$ that meet the corresponding conditions in the RMS resource pool. Remanufacturing providers need to optimize the selection of SRM according to their own conditions (see Figure 7).

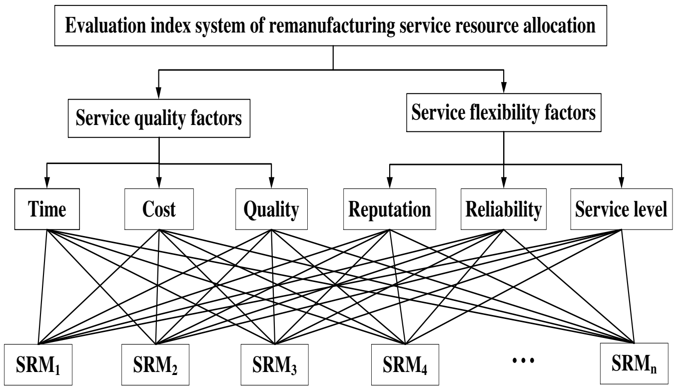

FIGURE 6. **Evaluation index system of RMSRA optimization model**

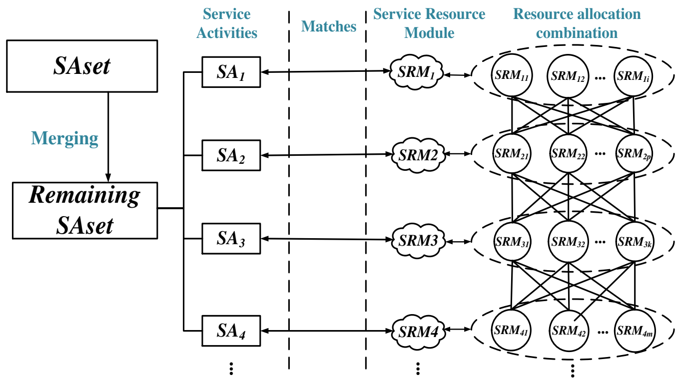

FIGURE 7. **Resource optimization allocation of service activities in GGRMS**

1) MODEL HYPOTHESIS

(1) This model is based on the merged service activity set SA_{set} and is applicable to all service activities SA_j $(j = 1,2,\cdots,n)$.
(2) The SA of different GGS can construct the connection relationship, and the SA that do not satisfy the $(i, i+1)$ relationship in the same GGS can also construct the connection relationship.
(3) The subjects considered under the RMSRA optimization model are remanufacturing providers, service resource providers and service integrators.

2) OBJECTIVE FUNCTION

$$\min SA_{set}T = \min\,[T_{wait} + T_{process} + T_{logistics}] = \sum_{i=1}^{n} T_{wait}(i) + \sum_{i=1}^{n} T_{process}(i) + \sum_{i=1}^{n-1} T_{logistics}(i, i+1) \quad (32)$$

Equation (32) is the total time objective function of the SA_{set}, where $\sum_{i=1}^{n} T_{wait}(i)$ represents the sum of the waiting times of the candidate SRM; $\sum_{i=1}^{n} T_{process}(i)$ represents the sum of processing time; $\sum_{i=1}^{n-1} T_{logistics}(i, i+1)$ represent the sum of logistics time between adjacent SAs.

$$\min SA_{set}C = \min\,[C_{logistics} + C_{process} + C_{connection}] = \sum_{i=1}^{n-1} C_{logistics}(i, i+1) + \sum_{i=1}^{n} C_{process}(i) + \sum_{i=1}^{n-1} C_{connection}(i, i+1) \quad (33)$$

Equation (33) is the objective function of total cost of the SA_{set}, where $\sum_{i=1}^{n-1} C_{logistics}(i, i+1)$ represents the sum of logistics costs of candidate SRM; $\sum_{i=1}^{n} C_{process}(i)$ represents the sum of processing costs; $\sum_{i=1}^{n-1} C_{connection}(i, i+1)$ represents the sum of connection costs between adjacent SA.

$$\min SA_{set}Q = \min\,\{\textstyle\sum_{i=1}^{n}[1 - Q_{qual\,rate}(i)]/n\} \quad (34)$$

Equation (34) is the total quality objective function of the SA_{set}. $Q_{qual\,rate}(i)$ refers to the qualified rate of SA completed by the ith candidate SRM.

$$\min Re = \min\,\{\textstyle\sum_{i=1}^{n}[1 - R_{reputation}(i)]/n\} \quad (35)$$

Equation (35) is the objective function of reputation, where $R_{reputation}(i)$ represents the reputation value of the ith service resource provider.

$$\min Te = \min \sum_{i=1}^{n} \omega_{res}[(1 - T_{res}(i))/n] + \omega_{tec}[(1 - T_{tec}(i))/n] \quad (36)$$

Equation (36) is the objective function of reliability, where $T_{res}(i)$ 、 $T_{tec}(i)$ represents the resource and technical reliability coefficients of the ith candidate service resource provider. $\omega_{res}, \omega_{tec}$ are the weight coefficients of the resource and technical reliability, respectively, and $\omega_{res} + \omega_{tec} = 1$.

$$\min Se = \min \sum_{i=1}^{n} \omega_{cap}\left[\frac{1 - S_{cap}(i)}{n}\right] + \omega_{eva}[(1 - S_{eva}(i))/n] \quad (37)$$

Equation (37) is the objective function of service level, where $S_{cap}(i), S_{eva}$ represents the service capability coefficient and service evaluation coefficient of the ith candidate service resource provider. $\omega_{cap}, \omega_{eva}$ are the weight coefficients of service capacity and service evaluation, and $\omega_{cap} + \omega_{eva} = 1$.

3) CONSTRAINT CONDITION

$$SA_{set}T \le \boldsymbol{T_{max}} \quad (38)$$

Equation (38) is the total time constraint, i.e., the total time to complete the SA_{set} shall not exceed the latest completion deadline $\boldsymbol{T_{max}}$ specified by the remanufacturing providers.

$$SA_{set}C \le \boldsymbol{C_{max}} \quad (39)$$

Equation (39) is the total cost constraint, i.e., the total cost of completing the SA_{set} shall not be higher than the highest budget expenditure $\boldsymbol{C_{max}}$ of the remanufacturing providers.

$$\sum_{i=1}^{n} Q_{qual\,rate}(i)/n \geq \boldsymbol{Q_{min}} \quad (40)$$

Equation (40) is the total quality constraint, i.e., the average completion quality of all SRM shall not be lower than the minimum expected quality $\boldsymbol{Q_{min}}$ of the remanufacturing providers.

$$\sum_{i=1}^{n} R_{reputation}(i)/n \geq \boldsymbol{Re_{min}} \quad (41)$$

Equation (41) is the total reputation constraint, i.e., the average reputation of all service resource providers shall not be lower than the lowest expected reputation of the remanufacturing providers $\boldsymbol{Re_{min}}$.

$$\sum_{i=1}^{n}[\omega_{res}\left(\frac{T_{res}(i)}{n}\right) + \omega_{tec}\left(\frac{T_{tec}(i)}{n}\right)] \geq \boldsymbol{Te_{min}} \quad (42)$$

Equation (42) is the total reliability constraint, i.e., the average reliability of all service resource providers shall not be lower than the minimum expected reliability of the remanufacturing providers $\boldsymbol{Te_{min}}$.

$$\sum_{i=1}^{n}[\omega_{cap}\left(\frac{S_{cap}(i)}{n}\right) + \omega_{eva}\left(\frac{S_{eva}(i)}{n}\right)] \geq \boldsymbol{Se_{min}} \quad (43)$$

Equation (43) is the total service degree constraint, i.e., the average service degree of all service resource providers shall not be lower than the minimum expected service degree of the remanufacturing providers $\boldsymbol{Se_{min}}$.

IV. MODEL SOLVING

A. ALGORITHM DESCRIPTION AND STEPS

Non-dominant Sorting Genetic Algorithm (NSGA) is a multi-objective optimization algorithm based on Pareto optimization. Drawing on genetic algorithm, NSGA hierarchizes individuals according to dominance and non-dominated relationships and operates individual selection, the excellent individuals therefore have a greater chance inheriting to the next generation. The problem of resource allocation optimization is a NP-hard. NSGA-II is an improved multi-objective optimization algorithm based on NSGA. Compared to NSGA, its improvements include the following aspects: 1) It proposes to reduce the complexity of calculation through fast non-dominated sorting; 2) It introduces an elite strategy to select the next generation population from the double population through the merger of the parent and the offspring to ensure that the excellent population individuals will not be lost in the evolution; 3) The crowding degree comparison operator is used to overcome the defect of artificially specifying shared parameters, and the individuals in the Pareto domain can be evenly extended to the entire Pareto domain. Other algorithms, such as particle swarm optimization (PSO) and simulated annealing algorithm (SAA), although they converge fast, they tend to fall into local optimal solutions. Ant colony algorithm (ACO), artificial fish colony algorithm (AFSA) and artificial bee colony algorithm (ABCA) will deviate from the optimal solution if the initial parameters are not well chosen. Therefore, the NSGA-II algorithm was selected to solve the model. The specific solution process is presented as follows:

Step 1: For each service activity, candidate service resource module is randomly selected for integer coding. Each coding position corresponds to the service activity candidate service number, and the coding value corresponds to the service activity candidate service resource module number, for example, the code 3-2-1-3-2-1-2-1-2 indicates that the selected service resource module is SRM_{13}-SRM_{22}-SRM_{31}-SRM_{43}-SRM_{52}-SRM_{61}-SRM_{72}-SRM_{81}-SRM_{92}.

Step 2: Under the constraint of Equations (38) ~ (43), variable x is limited in the search range, and the initial population S is generated randomly.

Step 3: According to the fitness function Equations (32) ~ (37), the non-dominated frontend sequencing of population S under different fitness functions is calculated, and then the crowding degree of individuals in each frontend is calculated according to the ranking.

Step 4: According to the non dominated sorting of population S in *Step 2* and the individual crowding degree in each frontend, the tournament function is used for selection operation, and then crossover and mutation operations are performed to generate new species group Q. Finally, the combined population SQ is obtained by combining with population S.

Step 5: According to the fitness function Equations (32) ~ (37), the non dominated frontend sequencing of population SQ under different fitness functions is calculated, and the crowding degree of individuals in each front-end is calculated respectively according to the order. Then, according to the optimal front-end individual coefficient, the population SQ is pruned to generate new species group newS.

Step 6: Repeat Steps 3 to 5 until g satisfies the maximum number of iterations g_{max}, output Pareto solution. The general process of solving the problem of optimal allocation of resources is shown in Figure 8, where g is the hereditary iterated algebra and g_{max} is the largest hereditary iteration algebra.

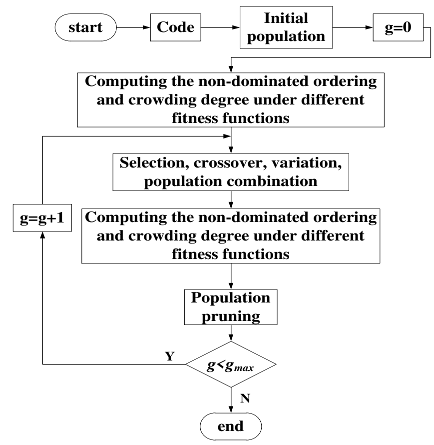

FIGURE 8. **The flow chart of NSGA-Ⅱ algorithm**

B. PARETO SOLUTION PROCESSING

In general, the solution of a multi-objective optimization problem is not unique, but there is an optimal solution set, i.e., the Pareto solution set. In order to allow remanufacturing providers to notice the difference in service resource combination more intuitively, the Pareto solution obtained is normalized, and the target weight value is assigned to sort the service resource module combination. The normalization process is given as follows:

for cost indicators:

$$\begin{cases} M_{iv}^{*} = \frac{M_{ivmax}-M_{iv}}{M_{ivmax}-M_{ivmin}} & M_{ivmax} \neq M_{ivmin} \\ M_{iv}^{*} = 1 & M_{ivmax} = M_{ivmin} \end{cases} \tag{44}$$

for benefit indicators:

$$\begin{cases} M_{iv}^{*} = \frac{M_{iv}-M_{ivmin}}{M_{ivmax}-M_{ivmin}} & M_{ivmax} \neq M_{ivmin} \\ M_{iv}^{*} = 1 & M_{ivmax} = M_{ivmin} \end{cases} \tag{45}$$

Therefore, the allocating degree of remanufacturing service resource module combination is denoted as:

$$\boldsymbol{M} = \sum_{i=1}^{6} \omega_i M_{iv}^{*} \tag{46}$$

The value of ω_i corresponding to each indicator is determined by the remanufacturing providers according to its own situation, and $\sum_{i=1}^{6} \omega_i = 1$.

V. CASE STUDY

By applying this method to the generalized growth of manual gearboxes, the feasibility and effectiveness of this method are verified, and the development of RMS to GGRMS is promoted. The case consists of three parts: GGS_{set} proposed, merging of redundant SA, RMSRA solution for remaining service activities.

A. GGS_{set} PROPOSED

The remanufacturing providers received a retired manual gearbox. Although the shapes and functions of the manual gearboxes produced by various automobile companies are different, they are basically composed of housing, transmission part, control part and synchronizer. This paper takes the manual gearbox produced by an automobile factory as an example (see Figure 9). The RMS integration platform formulates GGS_{set} based on the generalized decision-making method of [17], as shown in Table 2.

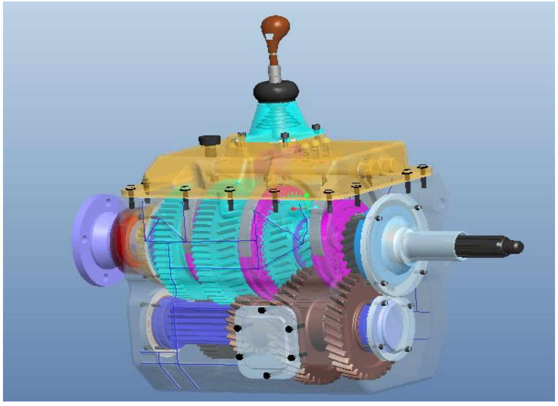

FIGURE 9. Manual gearbox parts drawing

B. MERGING OF REDUNDANT SA

For the evaluation of the coupling of service activities, a decision-making team composed of 8-$EVEs$ was invited to conduct the evaluation. These $EVEs$ include 4 experienced RMS activity operators, 2 service integration experts and 2 resource provider experts. The rough-fuzzy method is used to evaluate the coupling between each pair of service activities identified in Table 2. First, through Equations (2)-(16), the group linguistic coupling matrix of hardware resource coupling, human resource coupling, and software resource coupling are respectively transformed into the form of rough-fuzzy coupling matrix. Then, use Equations (17)-(25) to determine the weights of hardware resource coupling, human resource coupling, and software resource coupling to be 0.416, 0.311, and 0.273, respectively. Finally, using Equations (26) and (28), a clear comprehensive coupling degree matrix between each pair of service activities is shown in Table 3. The judgment threshold $\boldsymbol{\theta}$ is set to 0.85 in accordance with the standards of service providers and service integrators, and the results of various types of coupled service activities are shown in Table 4.

TABLE 2. Remanufacturing generalized growth scheme set

Object	SA_{set}	Growth mode
Gearbox	Recycle1- Disassemble2- Cleaning3-Classification4- Transport5	—
Housing	Assessment6-Pyrolysis pretreatment7-Roughing8- Cleaning9- Thermal Spray10- Finish machining11- Qualified inspection12- Reassemble13	Remanufactured into original components
1st main Gear	Cleaning14-Testing15-Assessment16-Roughing17-Shot peening18-Cleaning19-Finish machining20- Qualified inspection21- Reassemble22	Remanufactured into original components
2nd main Gear	Cleaning23- Testing24- Assessment25- Annealing before welding26- Laser cladding27- Roughing28- Heat treatment29- Finish machining30- Qualified inspection31- Optimize assembly32- Sales33- Transport34	Remanufactured into new components
3rd main Gear	Cleaning35-Testing36-Assessment37-Redesign38-Annealing before welding39-	Downgrade

	Roughing40- Shot peening41- Heat treatment42- Finish machining43- Qualified inspection44- Packing45- Sales46- Transport47	remanufacturing into new parts
4th main Gear	Cleaning48- Testing49- Assessment50- Annealing before welding51- Thermal Spray52- Heat treatment 53- Finish machining54- Qualified inspection55- Packing56	Remanufactured into original parts
5th main Gear	Cleaning57-Testing58-Assessment59-Redesign60-Annealing before welding61-Roughing62- Shot peening63- Heat treatment64- Finish machining65- Qualified inspection66- Packing67- Sales68- Transport69	Downgrade remanufacturing into new parts
Main drive Gear	Cleaning70- Testing71- Assessment72- Roughing73- Laser cladding74- Cleaning75- Finish machining76- Qualified inspection77- Reassemble78	Remanufactured into original components
Input Shaft	Cleaning79- Testing80- Assessment81- Redesign82- Roughing83- Thermal Spray84- Finish machining85- Qualified inspection86- Packing87- Sales88- Transport89	Downgrade remanufacturing into new parts
Intermediate Shaft	Cleaning90-Testing91-Assessment92-Thermal Spray93- Finish machining94- Qualified inspection95	Remanufactured into original parts
Output Shaft	Recycle96- Cleaning97- Transport98	As a blank
Synchronizer	Cleaning99- Testing100- Assessment101- Roughing 102- Laser cladding103- Finish machining104- Qualified inspection105- Reassemble106	Remanufactured into original parts
Synchronizer Cone	Recycle107- Cleaning108- Transport109	As a blank
Side bearing of differential	Cleaning110- Dimensional inspection 111- Roughing112- Qualified inspection113- Assemble with low-performance parts 114	Downgrade and remanufacture into low-performance parts

TABLE 3. **Comprehensive coupling degree between service activities**

	SA01	*SA02*	*SA03*	*SA04*	*SA05*	*SA06*	*SA07*	*SA08*	*SA09*	*SA10*	*SA11*	*SA12*	*SA13*	*SA14*	*SA15*	*SA16*	*SA17*	*SA18*	*SA19*	*SA20*	….	*SA112*	*SA113*	*SA114*
SA01	1.000	0.000	0.000	0.237	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	….	0.000	0.038	0.000
SA02	0.000	1.000	0.000	0.068	0.000	0.282	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.282	0.000	0.000	0.000	0.000	….	0.000	0.000	0.000
SA03	0.000	0.000	1.000	0.000	0.000	0.000	0.025	0.000	0.562	0.000	0.000	0.000	0.000	0.534	0.000	0.000	0.000	0.000	0.211	0.000	….	0.000	0.000	0.000
SA04	0.237	0.068	0.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	….	0.000	0.000	0.000
SA05	0.000	0.000	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	….	0.000	0.000	0.000
SA06	0.000	0.282	0.000	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000	0.170	0.000	0.000	0.150	0.908	0.000	0.000	0.000	0.000	….	0.012	0.000	0.000
SA07	0.000	0.000	0.025	0.000	0.000	0.000	1.000	0.049	0.025	0.000	0.000	0.000	0.000	0.025	0.000	0.000	0.000	0.000	0.025	0.000	….	0.000	0.000	0.000
SA08	0.000	0.000	0.000	0.000	0.000	0.000	0.049	1.000	0.000	0.000	0.068	0.000	0.000	0.000	0.000	0.000	1.000	0.000	0.000	0.068	….	1.000	0.000	0.000
SA09	0.000	0.000	0.562	0.000	0.000	0.000	0.025	0.000	1.000	0.000	0.000	0.000	0.000	0.783	0.000	0.000	0.000	0.000	0.427	0.000	….	0.000	0.000	0.000
SA10	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.214	0.000	0.000	….	0.000	0.000	0.000
SA11	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.068	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000	0.068	0.000	0.000	1.000	….	0.068	0.000	0.000
SA12	0.000	0.000	0.000	0.000	0.000	0.170	0.000	0.000	0.000	0.000	0.000	1.000	0.000	0.000	0.130	0.034	0.000	0.000	0.000	0.000	….	0.000	0.990	0.000
SA13	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	….	0.000	0.000	0.672
SA14	0.000	0.000	0.534	0.000	0.000	0.000	0.025	0.000	0.783	0.000	0.000	0.000	0.000	1.000	0.000	0.000	0.000	0.000	1.000	0.000	….	0.000	0.000	0.000
SA15	0.000	0.000	0.000	0.000	0.000	0.150	0.000	0.000	0.000	0.000	0.000	0.130	0.000	0.000	1.000	0.150	0.000	0.000	0.000	0.000	….	0.000	0.470	0.000
SA16	0.000	0.282	0.000	0.000	0.000	0.908	0.000	0.000	0.000	0.000	0.000	0.034	0.000	0.000	0.150	1.000	0.000	0.000	0.000	0.000	….	0.000	0.012	0.000
SA17	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000	0.000	0.000	0.068	0.000	0.000	0.000	0.000	0.000	1.000	0.000	0.000	0.068	….	1.000	0.000	0.000
SA18	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.214	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000	0.000	0.000	….	0.000	0.000	0.000
SA19	0.000	0.000	0.211	0.000	0.000	0.000	0.025	0.000	0.427	0.000	0.000	0.000	0.000	1.000	0.000	0.000	0.000	0.000	1.000	0.000	….	0.000	0.000	0.000
SA20	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.068	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000	0.068	0.000	0.000	1.000	….	0.068	0.000	0.000
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮		⋮	⋮	⋮
SA112	0.000	0.000	0.000	0.000	0.000	0.012	0.000	1.000	0.000	0.000	0.068	0.000	0.000	0.000	0.000	0.000	1.000	0.000	0.000	0.068	….	1.000	0.000	0.000
SA113	0.038	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.990	0.000	0.000	0.470	0.012	0.000	0.000	0.000	0.000	….	0.000	1.000	0.000
SA114	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.672	0.000	0.000	0.000	0.000	0.000	0.000	0.000	….	0.000	0.000	1.000

TABLE 4. Service activity coupling result

Type	Coupling SA	Type	Coupling SA
$Type_1$	{1,96,107}	$Type_{10}$	{15,24,36,49,58,71,80,91,100}
$Type_2$	{5,34,47,69,89,98,109}	$Type_{11}$	{18,41,63}
$Type_3$	{6,16,25,37,50,59,72,81,92,101}	$Type_{12}$	{26,39,51,61}
$Type_4$	{8,17,28,40,62,73,83,102,112}	$Type_{13}$	{27,74,103}
$Type_5$	{10,52,84,93}	$Type_{14}$	{29,42,53,64}
$Type_6$	{11,20,30,43,54,65,76,85,94,104}	$Type_{15}$	{33,46,68,88}
$Type_7$	{12,21,31,44,55,66,77,86,95,105,113}	$Type_{16}$	{38,60,82}
$Type_8$	{13,22,78,106}	$Type_{17}$	{45,56,67,87}
$Type_9$	{14,19,23,35,48,57,70,75}	$Type_{18}$	{79,90,97}

The cleaning agent and solvent of the cleaning service activity may vary from object to object. Therefore, the remanufacturing supplier will clean the similar or the same type of parts together in the actual operation, so the cleaning of the housing, gears and shafts cannot be merged. However, assessment and testing are based on professional and technical personnel's empirical judgment or simple inspection based on equipment, and do not distinguish between objects, so they can be merged together. The equipment and operators required for service activities such as laser cladding, shot peening, packaging, transportation, and sales are all fixed and will not change due to the changes in objects. The redesign process needs to combine internal and external factors. The internal factors include the structure and performance of the parts themselves, and the external factors include economy and energy consumption. Therefore, the redesign has strong complexity and diversity, and the redesign between GGSs cannot be merged.

C. RMSRA SOLUTION FOR REMAINING SERVICE ACTIVITIES

After the redundant service activities are merged, 29 independent service activities are left, and 29 service activities are reconnected in series. The relationship between connection time and connection cost is established between adjacent service activities according to the conditions of the remanufacturing providers. Since the target subject of service resource allocation is service activity and corresponds to it one-to-one, there is no need to consider the influence of the order of service activities. In addition, due to space limitation, it is impossible to show the resource optimization allocation process of all service activities one by one, only 9 service activities retained after the merger are selected as the display. On the RMS integration platform, according to the allocating mechanism, the candidate service resource module SRM_{np} (p represents the candidate service resource module corresponding to the service activity n) that meets the requirements is initially screened out, as shown in Table 5. See APPENDIX for the relevant parameters of the candidate service resource module.

TABLE 5. Candidate SRM corresponding to SA

Remaining SA_{set}	SA 1	SA 2	SA 3	SA 4	SA 5	SA 6	SA 7	SA 8	SA 9
Candidate SRM	SRM_{11}	SRM_{21}	SRM_{31}	SRM_{41}	SRM_{51}	SRM_{61}	SRM_{71}	SRM_{81}	SRM_{91}
	SRM_{12}	SRM_{22}	SRM_{32}	SRM_{42}	SRM_{52}	SRM_{62}	SRM_{72}	SRM_{82}	SRM_{92}
	SRM_{13}	SRM_{23}		SRM_{43}	SRM_{53}				

All parameters in the RMSRA optimization model are jointly determined by the remanufacturing providers and the RMS integrator according to the type and specific content of the SA. This paper assumes that the parameters in the model are as follows:

ω_{res}=0.4, ω_{tec}=0.6, ω_{cap}=0.7, ω_{eva}=0.3, T_{max}=15, C_{max} =1050, Q_{min} =0.90, Re_{min} =0.90, Te_{min} =0.90, Se_{min}=0.86.

The parameters in this experiment are mainly from a remanufacturing and service resource provider based in Xiangyang, Hubei, China, which are authentic and reliable values used in practice. The above parameters are used in the NSGA-Ⅱ algorithm, and the algorithm is implemented using Python. The parameters for this algorithm are initialized as follows: the population size is 20, the optimal frontend coefficient 0.3, the maximum genetic number 400, the crossover probability Pc 0.8, and the mutation probability Pm 0.03. Due to the large difference between cost and time fitness function values, no significant difference can be observed; we therefore only show the average fitness value of the population under the four objective functions of quality, reputation, reliability and service level (Figure 10),

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and show the Pareto frontier of the population under the factors of service quality and service flexibility (Figure 11(a) and (b)).

Using this algorithm to solve a non-inferior solution set, there are a total of 18 sets of service resource configuration combinations that meet the requirements, which are presented in Table 6.

The index weight of the service resource combination can be set according to the subjective preference of the remanufacturing providers. In this work, according to the combination weighting method in [49], the subjective preference coefficient is set to 0.5, so that we have $\omega_i = (0.2106, 0.2923, 0.1534, 0.1145, 0.1425, 0.0867)$. According to Equations (44)-(46), the allocating degree $\boldsymbol{M}$ of SRM_c of 18 groups of solutions is obtained as shown in Table 7.

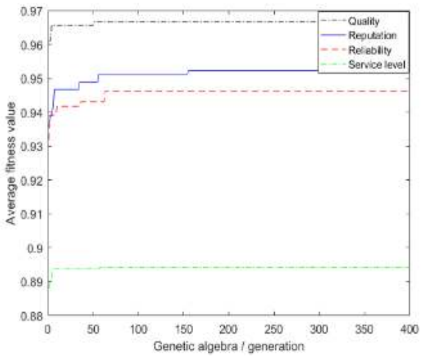

FIGURE 10. Average fitness of population under quality and service flexibility factors

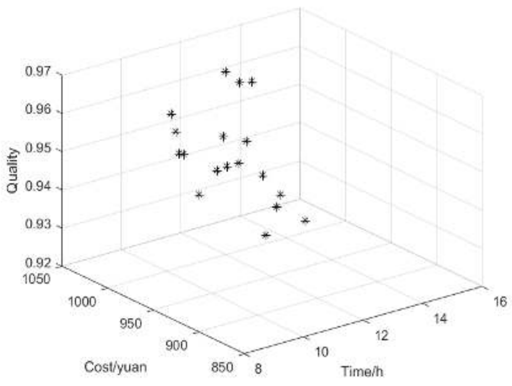

FIGURE 11. Pareto frontier of population under (a) Service quality factors

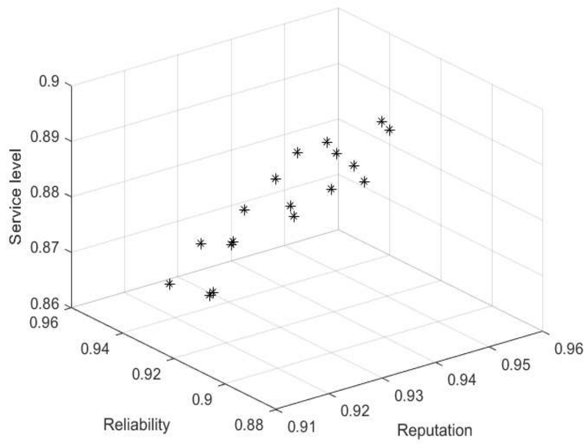

FIGURE 11. (b) Service flexibility factors

TABLE 7. Remanufacturing service resource combination allocating degree

Number	$\boldsymbol{M}$	Rank
$SRM_{com}1$	0.362	17
$SRM_{com}2$	0.399	14
$SRM_{com}3$	0.486	9
$SRM_{com}4$	0.381	16
$SRM_{com}5$	0.539	6
$SRM_{com}6$	0.481	11
$SRM_{com}7$	0.312	18
$SRM_{com}8$	0.439	12
$SRM_{com}9$	0.387	15
$SRM_{com}10$	0.485	10
$SRM_{com}11$	0.418	13
$SRM_{com}12$	0.725	2
$SRM_{com}13$	0.556	5
$SRM_{com}14$	0.727	1
$SRM_{com}15$	0.637	3
$SRM_{com}16$	0.625	4
$SRM_{com}17$	0.531	7
$SRM_{com}18$	0.509	8

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TABLE 6. Pareto solution of NSGA-II algorithm

Number	SRM_{com}	Time/h	Cost/yuan	Quality	Reputation	Reliability	Service level
$SRM_{com}1$	112331121	12.300	1020.000	0.939	0.926	0.938	0.863
$SRM_{com}2$	112131112	12.300	1028.000	0.959	0.917	0.935	0.868
$SRM_{com}3$	131122211	12.300	970.000	0.943	0.939	0.906	0.887
$SRM_{com}4$	132332112	11.600	1047.000	0.952	0.924	0.935	0.865
$SRM_{com}5$	211122221	12.200	963.000	0.929	0.949	0.920	0.892
$SRM_{com}6$	211322112	12.900	1007.000	0.947	0.940	0.934	0.885
$SRM_{com}7$	211322221	14.400	1023.000	0.924	0.952	0.924	0.888
$SRM_{com}8$	212331122	11.700	1042.000	0.942	0.928	0.946	0.880
$SRM_{com}9$	212332222	12.200	1036.000	0.931	0.941	0.939	0.874
$SRM_{com}10$	231121212	11.100	1026.000	0.951	0.934	0.911	0.894
$SRM_{com}11$	231131112	12.900	1030.000	0.962	0.927	0.927	0.880
$SRM_{com}12$	311122112	10.300	931.000	0.956	0.931	0.924	0.885
$SRM_{com}13$	311122211	11.400	894.000	0.942	0.912	0.908	0.873
$SRM_{com}14$	311122212	10.900	905.000	0.949	0.938	0.914	0.890
$SRM_{com}15$	311331112	10.400	951.000	0.960	0.927	0.931	0.874
$SRM_{com}16$	311331212	9.900	978.000	0.953	0.933	0.922	0.879
$SRM_{com}17$	331121211	11.000	967.000	0.949	0.929	0.898	0.890
$SRM_{com}18$	331131112	12.300	982.000	0.967	0.921	0.920	0.877

The comparison of the comprehensive allocating degree $\boldsymbol{M}$ of all SRM_c is shown in Figure 12.

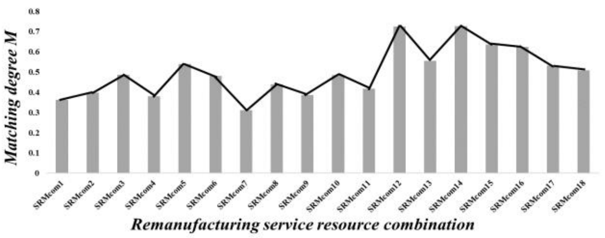

FIGURE 12. Allocating degree comparison

D. RESULT AND DISCUSSIONS

1) ADVANTANGES OF GENERALIZED GROWTH

a) Parts with higher residual value can be remanufactured into not only original parts but also other new parts through size changes or functional embedding. It can be sold to other suppliers, or be optimized and matched with other parts and remanufactured into new components or new products.

b) Damaged or low residual value parts and components can be used as blanks for other new parts and components; and parts and components that cannot be restored in size can be used for other purposes after redesigned or downgraded. For example, the intermediate shaft of a manual gearbox can be redesigned and reprocessed under appropriate conditions, and finally remanufactured into an optical axis; the bearing seat can be added with a signal device to achieve functional improvement. The generalized growth of remanufacturing has changed the previous single remanufacturing mode --- converting products into multi-level components, from high-performance original components to low-performance new components. It realizes the comprehensive growth of multi-granularity of retired mechanical products, improves the residual value of products, components and parts, reduces the energy consumption caused by excessive disassembly and remanufacturing, and therefore maximizes the utilization of retired resources. Moreover, generalized growth is applicable not only to mechanical products but also to other electronic products or complex physical products.

2) COUPLING COMPARISON

According to the results shown in Table 4, the number of redundant service activities $NC_{SA} = 85$, and the type of coupled service activity $r = 18$. Therefore, the overall allocating rate improved by the GGS_{set} can be denoted as follows:

$$E_m = NC_{SA}/TN_{SA} = 85/114 = 0.7456$$

The improved allocating efficiency of each type of coupled service activity is shown in Table 8.

TABLE 8. Improved allocating rate of various types of coupled service activities

$Types$	E_R	$Types$	E_R
$Type_1$	0.667	$Type_{10}$	0.889
$Type_2$	0.857	$Type_{11}$	0.667
$Type_3$	0.900	$Type_{12}$	0.750
$Type_4$	0.889	$Type_{13}$	0.667
$Type_5$	0.750	$Type_{14}$	0.750
$Type_6$	0.900	$Type_{15}$	0.750
$Type_7$	0.909	$Type_{16}$	0.667
$Type_8$	0.750	$Type_{17}$	0.750
$Type_9$	0.875	$Type_{18}$	0.667

Of course, in real life, the time for allocating resources for each service activity is different. This paper is to simplify the complexity of the problem and to show the improvement of resource allocating rate more intuitively. Therefore, considering the coupling constraints of remanufacturing service activities in the GGRMS mode can reduce the complexity of the RMSRA process and greatly improve the efficiency of resource allocation in the GGRMS mode.

3) MODEL RESULTS

According to this process in this case study, all resource allocation combinations of the remaining 29 SA can be obtained, and remanufacturing providers can reasonably select service resource module combinations based on their own conditions. It is worthy to note that if the service cost is only used as the evaluation index, then $SRM_{com}13$ is the optimal combination of service resources module. From the perspective of the flexibility of service resources, the flexibility value of the service resource combination is lower than that of some other combinations. For example, in the actual RMS process, the service resource combination may not really complete all the service activities due to uncertain factors. This will also affect the resource allocation of other merged service activities. Therefore, to reduce the risk of optimal allocation and the loss caused by uncertain resources factors, this service resource combination is not desirable. Chosen from the overall allocating degree $\boldsymbol{M}$ of the generalized service mode, the $SRM_{com}12$ and $SRM_{com}14$ solutions of the service resource allocation model have higher service quality and service flexibility, and are less impacted by uncertain factors when completing service activities; therefore, they are suitable to be considered as the optimal solution for service resource demand enterprises.

4) IMPLICATIONS

This paper studies the optimal allocation of remanufacturing service resources for the generalized growth of retired mechanical products, and provides a new perspective for the field of remanufacturing services. As opposed to the traditional remanufacturing modes that treat entire product as a remanufacturing unit. GGRMS maximizes the residual value of the retired mechanical products. Under this mode, to improve the efficiency of resource allocating, it is required to find redundant service activities; in order to ensure the interests of both the service providers and service integrators, resource flexibility factors and service stability have a notable promotion effect on the healthy development of RMS.

VI. CONCLUSION AND FUTURE WORK

RMS is a new manufacturing mode of remanufacturing with service. Because of its high efficiency and low energy consumption, it has received extensive attention from both academia and industry. RMSRA is crucial to promote the development and management of RMS. GGRMS has changed the traditional remanufacturing method, relying on the service process of a third-party remanufacturing service integrator. Depending on the credit guarantee mechanism of mutual monitoring of various stakeholders under the blockchain economic model, it breaks the limitation of outsourcing individual activities such as remanufacturing design or processing to a fixed service provider. Support the outsourcing and crowdsourcing of all service activities under the optimal conditions of the entire service process, which will become the core development content of the GGRMS operation model. And it promotes the development from services supported by traditional information technology to services relying on new information and intelligent technology. It provides guidance for the value-added of RMS and for the upgrading of remanufacturing technology, enriches the RMS.

This paper has three main contributions. First, GGRMS changes the traditional single remanufacturing mode that treats entire products as remanufacturing units. The multi-granularity generalized growth scheme set of different parts and components of the same product is proposed to maximize the residual value of retired mechanical products. Second, considering the coupling constraints of remanufacturing service activities, in order to improve resource allocating efficiency, the redundant service activities are merged before allocating resources, which greatly improves the efficiency of service resource allocating. Finally, the RMSRA method is optimized, different from traditional RMSRA, this paper fully considers the interests of both service providers and service integrators in the GGRMS environment. The situation that only takes the service quality factor as the objective function is changed, and the service flexibility factor of the service resource provider is added, and the NSGA-Ⅱ algorithm is used to solve the model case. The calculation results show that the efficiency of resource allocating after the combined service activities is greatly improved, which provides guidance for resource services under the GGRMS model.

However, this model not consider the mutual influence between targets and some uncertain factors in the combination of resource and service configuration, and cannot fully fit realistic scenarios. Moreover, the connection relationships of the service activities among different GGSs may be more complicated, and the judgment of coupled service activities also has certain subjective factors. Therefore, future work should include combining the dynamic influencing factors between the goals, and defining the connection relationship of the service activities among different schemes that is more in line with reality. In addition, considering the high uncertainty of GGRMS and the superiority of data mining, a database of various service activities will be considered in the future. Future work also includes adopting deep learning methods to explore the coupling relationships between service activities. This will enable RMSRA to further unleash potential in GGRMS.

APPENDIX

Candidate SRM	Next level candidate SRM	Processing time /h	Logistics time /h	Waiting time /h	Processing cost /yuan	Logistics cost/yuan	Connection cost /yuan	Qualified rate	Corporate reputation	Resource reliability	Technical reliability	Service capacity	Service evaluation
SRM_{11}	SRM_{21}	0.3	0.4	0.3	110	30	8	0.98	0.93	0.99	0.89	0.88	0.91
	SRM_{22}		2.0			90	7						
	SRM_{23}		0.5			40	12						
SRM_{12}	SRM_{21}	0.2	0.2	0.6	120	20	12	0.95	0.95	0.96	0.93	0.93	0.98
	SRM_{22}		0.3			25	15						
	SRM_{23}		0.4			35	11						
SRM_{13}	SRM_{21}	0.3	0.2	0.1	90	35	11	0.99	0.90	0.98	0.82	0.91	0.93
	SRM_{22}		2.3			70	12						
	SRM_{23}		0.2			20	8						
SRM_{21}	SRM_{31}	0.4	0.1	0.1	40	8	11	0.90	0.92	0.89	0.99	0.83	0.99
	SRM_{32}		0.4			30	4						
SRM_{22}	SRM_{31}	0.3	0.6	0.2	38	50	12	0.98	0.96	0.98	0.88	0.85	0.92
	SRM_{32}		1.2			80	7						
SRM_{23}	SRM_{31}	0.2	0.4	0.4	45	45	11	0.92	0.90	0.85	0.91	0.91	0.81
	SRM_{32}		0.5			55	9						
SRM_{31}	SRM_{41}	0.4	1.8	0.2	150	10	8	0.99	0.98	0.90	0.93	0.91	0.88
	SRM_{42}		0.6			80	11						
	SRM_{43}		2.6			20	20						
SRM_{32}	SRM_{41}	0.5	2.4	0.2	120	80	11	0.95	0.89	0.99	0.91	0.82	0.91
	SRM_{42}		2.0			90	9						
	SRM_{43}		2.6			50	10						
SRM_{41}	SRM_{51}	0.4	0.4	0.2	50	40	13	0.94	0.92	0.95	0.92	0.88	0.78
	SRM_{52}		0.6			30	8						
	SRM_{53}		2.2			50	15						
SRM_{42}	SRM_{51}	0.5	0.4	0.3	40	35	10	0.91	0.94	0.91	0.98	0.86	0.81
	SRM_{52}		0.6			0	12						
	SRM_{53}		0.6			30	8						
SRM_{43}	SRM_{51}	0.1	0.5	0.1	60	30	9	0.90	0.95	0.93	0.99	0.79	0.89
	SRM_{52}		2.4			60	6						
	SRM_{53}		0.3			20	14						
SRM_{51}	SRM_{61}	0.4	0.5	0.3	72	16	9	0.98	0.95	0.99	0.93	0.88	0.98

	SRM$_{62}$		0.8			24	14						
SRM$_{52}$	SRM$_{61}$	0.4	0.4	0.3	38	20	11	0.95	0.93	0.96	0.89	0.93	0.91
	SRM$_{62}$		0.2			22	7						
SRM$_{53}$	SRM$_{61}$	0.3	0.3	0.2	45	10	18	0.99	0.92	0.98	0.97	0.83	0.88
	SRM$_{62}$		0.5			16	20						
SRM$_{61}$	SRM$_{71}$	0.5	1.1	0.1	120	30	12	0.94	0.90	0.92	0.82	0.83	0.93
	SRM$_{72}$		0.6			50	10						
SRM$_{62}$	SRM$_{71}$	0.2	0.8	0.6	114	50	12	0.90	0.96	0.89	0.88	0.83	0.92
	SRM$_{72}$		1.4			20	7						
SRM$_{71}$	SRM$_{81}$	0.4	0.2	0.3	50	40	9	0.98	0.92	0.98	0.99	0.85	0.87
	SRM$_{82}$		0.6			30	11						
SRM$_{72}$	SRM$_{81}$	0.4	0.4	0.1	60	35	13	0.92	0.98	0.85	0.93	0.91	0.88
	SRM$_{82}$		0.6			30	8						
SRM$_{81}$	SRM$_{91}$	0.6	1.6	0.2	48	30	7	0.99	0.90	0.90	0.91	0.91	0.81
	SRM$_{92}$		0.9			30	8						
SRM$_{82}$	SRM$_{91}$	0.1	2.0	0.5	56	80	12	0.91	0.95	0.91	0.99	0.86	0.89
	SRM$_{92}$		1.2			90	10						
SRM$_{91}$	-	1.0	2.2	0.3	50	50	0	0.90	0.95	0.92	0.85	0.91	0.88
SMR$_{92}$	-	0.8	1.8	0.2	60	60	0	0.96	0.95	0.98	0.91	0.88	0.97

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