RESEARCH ON MODULE PARTITION FOR REMANUFACTURING PARTS TO BE ASSEMBLED

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ABSTRACT

To solve the technical, economic and environmental problems in the remanufacturing process of decommissioned machine tools, this study proposes a module partition method for remanufacturing retired machine tools. Through an analysis of the economic, accuracy, environment-friendly, and functional and physical interactivity principles, this study applies the fuzzy cluster method (FCM) to analyse the modularity of the components to be assembled. It establishes the correlation matrix between the parts, from which a module division scheme is obtained. Finally, a case study is presented to verify the feasibility of the module division method.

OPSOMMING

Om die tegniese, ekonomiese en omgewingsprobleme in die hervervaardigingsproses van masjiengereedskap wat buite gebruik geraak het, op te los, stel hierdie studie 'n moduleverdelingsmetode voor vir die hervervaardiging van sulke masjiengereedskap. Deur 'n ontleding van die ekonomiese, akkuraatheid, omgewingsvriendelike en funksionele en fisiese interaktiwiteitsbeginsels, pas hierdie studie die "fuzzy cluster" metode (FCM) toe om die modulariteit van die komponente wat saamgestel moet word, te analiseer. Dit bepaal die korrelasiematriks tussen die dele, waaruit 'n module-verdelingskema verkry word. Ten slotte word 'n gevallestudie aangebied om die uitvoerbaarheid van die module-indelingsmetode te verifieer.

1   INTRODUCTION

Product modularisation is an effective way to achieve rapid product design [1]. Module partition is the fundamental basis of product modularity. Module division can support green manufacturing to meet the needs of green production, environmental friendliness, and rapid product development. Reasonable module classification can facilitate disassembly for recycling and maintenance replacement, reduce the number of parts, simplify the product structure, and improve product reusability and reconfigurability[2],[3]. The module partition methodology allows individual components to be combined into logical units that are relatively functionally independent, resulting in efficient product upgrades, reduced complexity, lower costs, and regionalised management[1],[4]. At present, domestic and foreign research institutions have made some progress in module partition, and studies have included module partition for the product life cycle, for green design, for environmental awareness, for remanufacturing possibility, for disassembly, for maintenance, and for reuse[5].

However, so far most of the studies have not involved a modular study of the remanufactured parts pool to be assembled. The remanufacturing of retired machine tools is strongly related to module classification. The module partition of remanufactured parts to be assembled can classify many parts, improve assembly efficiency, decrease assembly cost, and so on. Therefore, this paper proposes a module division method for remanufactured parts to be assembled. The method is based on a combination of qualitative and quantitative analyses to study the characteristic attributes of remanufactured parts to be assembled in

remanufacturing machine tools; it constructs a comprehensive correlation matrix of parts to be assembled; and it uses a fuzzy clustering analysis method to classify modules.

The rest of the paper is organised as follows. Section 2 presents the main recent studies on module partitioning and on the module partitioning of retired machine tools. Section 3 introduces the principles of building a module partition model for remanufactured parts to be assembled and the cluster analysis method. Section 4 presents the steps of applying the fuzzy cluster analysis method combined with the module classification model to find out the module classification scheme and to apply it to a practical case. Finally, conclusions are stated in Section 5.

2   LITERATURE REVIEW

There has been a large amount of literature in the field of module partitioning, both nationally and internationally; and remanufacturing is receiving more and more attention as an important part of green manufacture. In the remanufacturing system, it is valuable for both the factory and the customer to be able to have an effective module classification. This paper will review the literature in terms of module partition and the remanufacturing module partition of retired machine tools.

2.1   Module partition

From a supply chain management perspective, Inoue *et al.*[6] proposed a modular design approach that considered both sustainability and supplier selection, and evaluated the designed modularisation strategy in respect of economic cost, environmental load, component quality, and procurement lead time. From the perspective of the interface relationship between the advantages and disadvantages of the parts, Zhao *et al.*[7] performed the module division based on the functional qualitative hierarchical decomposition, considered the interface dependencies of the parts, and used the 'information entropy' to evaluate the module division scheme. From the perspective of product design requirements, Zhang *et al.*[8] established a comprehensive correlation matrix of parts based on the function—principle—behaviour—structure, and then used a combination of the gap statistics method and a self-organising mapping neural network to classify the product parts into modules. This method put forward a new idea for the module classification of other complex products. Also in aspect of complex product parts, Jia *et al.*[9] proposed a fuzzy evidential reasoning algorithm to fuse the functional correlation, the linkage correlation, and the physical correlation among parts, established a fuzzy mathematical model, and solved it with a fuzzy non-dominated discrete particle swarm algorithm, given that complex product module division largely depends on the correlation relationship among parts. The method of Jia *et al* can effectively deal with the transformation and transfer of uncertain information in the process of complex product module division. Yin *et al.*[10] proposed a module classification method based on a fuzzy diagram and an evaluation method based on D-S evidence theory from service modules, and argued that the combination of fuzzy diagram and evidence theory can provide specific ideas and guidance for service module classification. From the perspective of complex mechanical products module division and result assurance difficulties, Zhang *et al.*[11] similarly established a weighted complex network to express the structure of complex mechanical products, then reused the local computational relationships between parts using interval-valued intuitionistic fuzzy sets, and proposed an improved population improvement algorithm to achieve the module division of complex mechanical products.

In order to solve the problem of difficult mechanical CAD assembly model retrieval and the low level of model reuse, Han *et al.*[12] analysed and evaluated the association strength between assemblies in terms of assembly structure, function, and process. Based on this, they proposed a group detection algorithm with greedy ideas, so as to realise the modularisation of mechanical CAD assembly models. This method can quickly and accurately identify the module structure in CAD assembly models and improve the reuse of complex CAD assembly models. Wei *et al.*[13] found that most of the existing module partitioning methods neglected the design factor of customer preference, so that study used the fundamental principles of robust design for module partitioning to make it less sensitive to dynamically changing customer preferences. Yang *et al.*[14] considered the customer needs for electric heaters and the changing market demand, combined the characteristics of each stage of the product life cycle, and established the design principles of module division for recycling-oriented products in terms of service life analysis, material compatibility, recyclable economy, environmental impact, and functional and physical interaction; after that they solved the design principles with a fuzzy clustering algorithm. However, since the module division method covered the whole product life cycle, there may be local functional or structural conflicts after the module division. Chen[15] proposed a fuzzy cluster analysis based on the minimum and maximum division of product modules, with the minimum division subset as sub-modules for module aggregation and the maximum division subset as a module set for fuzzy cluster analysis; but that study only considered the correlations of the geometric,

functional, and physical relevance of the component parts of the product without further considering the influence of other factors. Li *et al.*[16] found that downstream product development stage considerations could not be used for module delineation during the conceptual design phase, and therefore introduced a new method to delineate the functional modules of complex products by using weighted and directed complex networks for community detection. Finally, a case study was carried out to delineate the modules and to validate the effectiveness of the method.

2.2   Module partition of remanufacturing of retired machine tools

From the perspective of the reconfigurability theory of computer numerical control(CNC) machine tools, Wang *et al.*[17] analysed and modularised the design of deep-hole components in terms of both module division and reconfigurability, and solved the key challenges of modularised machine design on this basis. From the viewpoint of the high variability of end-of-life product quality in the remanufacturing system, Zhou *et al.*[18] proposed a model that considered the impact of quality uncertainty on carbon emissions and divided the problem solution process into two sub-problems: the sequencing problem and the remanufacturing problem. In the sequencing problem, the optimal threshold of remanufacturing processing time was derived using the dichotomous method; in the remanufacturing method, the optimal acquisition and remanufacturing quantities were obtained using the optimal sequencing strategy. No multi-product remanufacturing system was considered, and this study only considered product item manufacturing systems with quality uncertainty and random demand. Fadeyi *et al.*[19] developed an optimisation model from a remanufactured product service system perspective to determine the module variants in the product that should be included in several available module variants, to complete the pairwise evaluation of modules, and to obtain the compatibility index of the module pairs by a fuzzy reasoning system. Zhang *et al.*[20] started from the economic, technical, and environmental aspects of the remanufacturing process, considered the impact of carbon emissions in the module division process, established a fuzzy correlation matrix between CNC machine tool parts, and realised the module division to achieve the effect of easy remanufacturing processing, cost reduction, and environmental damage reduction. From the product multiple life cycle viewpoint, Liu *et al.*[21] considered the following four principles: the principle of material selection and configuration; the principle of the use phase; the principle of the remanufacturing processing phase; and the principle of the functional and physical independence of the module. The study used the fuzzy cluster analysis method to construct a comprehensive correlation matrix for the module division of product remanufacturing design through quantitative analysis. Tchertchian *et al.*[22] built a modular grouping explorer (MGE) tool from an end-of-life perspective that could group remanufacturable and recyclable modules using reliability and obsolescence criteria, and validated the effectiveness and feasibility of the MGE tool with a case study. However, the module segmentation method failed to take into account the disassembly cost and environmental impact.

In response to the problem that the modular design method for green remanufacturing cannot obtain a unique division scheme, Bo *et al.*[23] evaluated the product module division scheme from the perspective of green remanufacturing, which needed to consider each stage of development, manufacturing, application, and recycling, and to analyse the correlation between parts from three perspectives — physical, environmental, and cost, to rank the module division scheme according to the principle of 'high cohesion and low coupling', finally to select the optimal module division scheme.

The literatures reviewed above are based on the module design from the perspective of complex product parts, user requirements, and remanufacture ability at the end of a product's life, but not on the module design of the parts to be assembled in the parts library consisting of reused parts, remanufactured parts, and purchased new parts. In the study of the parts library, Cao *et al.*[24] proposed the classification of remanufactured parts based on modularity theory and customised design for customer needs, and the remanufacturing of scrap parts into a customised part for prioritisation, but he did not elaborate on the classification. To create an inventory collection of each part, Liu *et al.*[25] proposed an alternative reassembly classification based on the characteristics of recycled parts and reassembly by grading the corresponding reassemblies to establish each part's inventory features, and improved the accuracy of remanufactured products. Liu *et al.* [26] classified the remanufactured parts into three classes according to their accuracy. Ma[27] classified the components in a modular way, and divided them into Class I and Class II components based on the importance of the components, whether they were standard or non-standard, and their component relatedness.

From the studies reviewed above, it can be seen that the research on the module classification of components to be assembled in the remanufactured parts library is relatively weak. Therefore, this paper analyses the module division of the parts to be assembled in the remanufactured parts library, and then

uses the fuzzy cluster analysis method to analyse the module division of the parts to be assembled from four perspectives: economy, accuracy, functional and physical interaction, and environmental friendliness.

3   PROBLEM DEFINITION AND MATHEMATICAL MODEL

3.1   Module division process based on remanufacturing

Module division is a method of the modular design of parts in the remanufactured parts library by considering the stages of recycling, testing, cleaning, remanufacturing, reassembling, and analysing the correlation between parts in terms of cost, accuracy, and environmental friendliness from the perspective of the user's needs. In this paper, according to the design principle of 'high cohesion and low coupling', the parts in the remanufactured parts library are divided into modules. Figure 1 shows the module division process of machine tool remanufacturing.
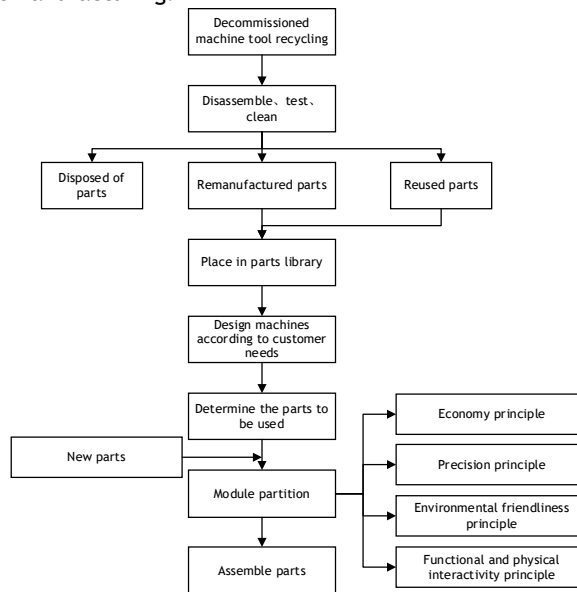

Figure 1: The process of dividing the remanufacturing modules of machine tools

3.2   Calculation of economy-related factors based on the principle of economy

In the parts-to-be-assembled library, it is necessary to divide some parts with the same or similar cost attributes into the same module. Moreover, the purpose of grouping parts to be assembled with similar cost attributes is to reduce assembly costs by more quickly and accurately selecting the lowest cost parts that meet the quality and accuracy conditions during the subsequent matching process.

In the parts-to-be-assembled library, the cost attributes of the parts should include the cost of disassembling the retired machine after recycling, the cost of cleaning and testing, and the cost of the remanufacturing process. Among them, the cost of disassembly after recycling consists of the labour cost during disassembly and the cost of the consumption of disassembly tools. The cost of cleaning and testing is composed of both labour and tool costs. The cost of the remanufacturing process includes the processing cost of remanufactured parts and the cost of purchasing new parts. The cost models are as follows:

$$C_E = C_D + C_C + C_R \tag{1}$$

where：

$$C_D = T_d C_d + C_{cr1} \tag{2} [28]$$

$$C_C = T_c C_c + C_{cr2} \tag{3}$$

$$C_R = \sum_{k=1}^{n} T_{r,k} C_{r,k} + C_N \tag{4} [29]$$

where C_E indicates the total cost of the remanufacturing stage of the parts to be assembled; C_D indicates the disassembly cost after recycling; C_C indicates the parts' cleaning and testing cost; and C_R indicates the processing cost of the remanufacturing. Among them, T_d shows the average disassembly time of part i; C_d denotes the disassembly unit time cost; C_{r1} denotes the disassembly tool consumption cost; T_c shows the average cleaning and inspection time of part i; C_c denotes the cleaning and inspection unit time cost; C_{r2} denotes the cleaning and inspection tool consumption cost; $T_{r,k}$ shows the total time spent in k processes for the remanufacturing of part i; $C_{r,k}$ denotes the cost per unit time of remanufacturing process; and C_N denotes the cost of purchasing new parts.

In this paper, the annual depreciation[30] will be used to represent the consumption cost of disassembly tools and the cost of testing tools. The cleaning cost is the cost of the cleaning agent.

Annual depreciation amount = (value of fixed assets - depreciated amount) ☐ annual depreciation rate

Annual depreciation rate = 2 / depreciable years☐100%

Define the economic correlation factor between parts i,j to be installed as

$$I_{e(i,j)} = \frac{\min(C_{Ei}, C_{Ej})}{\max(C_{Ei}, C_{Ej})}$$

（5）

where C_{Ei}, C_{Ej} are the total costs of the remanufacturing phase for parts i,j to be assembled respectively.

3.3 Correlation factor calculation based on accuracy principle

In a parts-to-be-assembled library, it is necessary to divide some parts with similar fitting accuracy levels into the same module. Dividing parts to be assembled with similar accuracy levels into the same module facilitates fast and efficient part matching. Suppose the fit size range of part i to be assembled is (X_{-d}^{+d}, β^2), which is divided into five grades, and λ=2d/5. So the fit size range of the part i is [x-d+(i-1)λ, x-d+iλ][25]. The specific grade division is shown in Table 1:

Table 1: Accuracy classification level

Grade no.	Third-grade accuracy	Second-grade accuracy	First-grade accuracy	Second-grade accuracy	Third-grade accuracy
Size range	$[x-d, x-\frac{3}{5}d]$	$[x-\frac{3}{5}d, x-\frac{1}{5}d]$	$[x-\frac{1}{5}d, x+\frac{1}{5}d]$	$[x+\frac{1}{5}d, x+\frac{3}{5}d]$	$[x+\frac{3}{5}d, x+d]$
Material type	Mostly reused parts	Mostly remanufactured parts	Mostly new parts	Mostly remanufactured parts	Mostly reused parts

Generally, for the same part to be assembled, in the case of meeting the range of fit dimensions, and based on the principle of the lowest cost, the reused parts should be selected first, followed by the remanufactured parts, and finally the new parts.

For any part i, j, the correlation factor of the fit dimensional accuracy is

$$I_{a(i,j)} = r_a = \frac{\min(AC_i, AC_j)}{\max(AC_i, AC_j)}$$

（6）

where, AC_i, AC_j are the respective fit size level of parts i, j to be assembled. When r_a=1, it means that the material type of parts i, j to be assembled is the same.

3.4 Calculation of carbon emission-related factors based on the principle of being environmentally friendly

We have been promoting energy conservation and reduced emissions, of which carbon emissions have a great impact on the environment. In the library of parts to be assembled, it is necessary to divide some parts with similar carbon emissions into the same module. The carbon emissions that come with the parts

to be assembled include those from disassembling, cleaning and testing, and remanufacturing. The carbon emissions from remanufactured are the sum of carbon emissions from reused parts, remanufactured parts, and new parts. As the manufacturing process for new parts is fixed, the carbon footprint is a fixed value, which is determined by the company.

$$CE = CE_D + CE_C + CE_R \tag{7}$$

in which:

$$CE_D = (\sum_{a=1}^{b} E_{Da} \times t_{Da}) \times CEF_{lco_2} \times GWP_{co_2} \tag{8}$$

$$CE_C = \sum_{s=1}^{t} E_{rs} \times CEF_{dco_2} \times GWP_{co_2} + \sum_{c=1}^{m} P_{Cc} \times t_{Cc} \times CEF_{eco_2} \times GWP_{co_2} \tag{9}$$

$$CE_R = w_1 \times CE_U + w_2 \times CE_R + w_3 \times CE_N$$
$$= w_1 \times CE_U + w_2 \times (\sum_{e=1}^{h} P_{Re} \times t_{Re}) \times CEF_{co_2} \times GWP_{eco_2} + w_3 \times CE_N \tag{10}$$

$$w_1 + w_2 + w_3 = 1 \tag{11}$$

$$w_i = \begin{cases} 0, & unselected \\ 1, & selected \end{cases} \tag{12}$$

In Eq. (7) ~ Eq. (10), the specific symbols and meanings are shown in the following table. w_1、w_2、w_3 indicate the weights of reused parts, remanufactured parts, and new parts.

Table 2: Symbols and meanings

Symbol	Meaning
CE	Total carbon emissions of parts to be installed
CE_D	Dismantling carbon emissions
CE_C	Cleaning and testing carbon emissions
CE_R	Remanufacturing carbon emissions
E_{Da}	Energy consumption per unit time of disassembly for type ath connection method
t_{Da}	Type ath coupling method disassembly time
CEF_{lco_2}	CO₂ emission factors in lubricant consumption components
GWP_{co_2}	The warming potential of CO_2 [31]
P_{Cc}	Power of the cth machine at the time of testing
t_{Cc}	Time of the cth machine at the time of testing
E_{rs}	Cleaning dose for the sth machine
GEF_{dco_2}	Carbon dioxide emission factors in cleaning agent
CEF_{eco_2}	Carbon dioxide emission factors in electricity consumption components
CE_U	Carbon emissions from reused parts
CE_N	Carbon emissions from new parts
P_{Re}	Power of the eth unit at remanufacturing
t_{Re}	Time of the eth unit at remanufacturing

Define the carbon emission correlation factor between parts i, j to be assembled as

$$I_{c(i,j)} = \frac{\min(CE_i, CE_j)}{\max(CE_i, CE_j)} \tag{13}$$

where CE_i , CE_j are the respective carbon emissions of the parts to be assembled i, j.

3.5 Interaction factor analysis based on the principle of functional and physical interactivity

In the library of parts to be assembled, it is necessary to divide some parts with strong functional and physical independence into the same module. The functional correlation between parts refers to the degree of coordination between two parts to accomplish the same function. The physical correlation between two parts refers to whether there is energy flow, information flow, material flow, etc.[9]. The basic conditions for the module division of the parts library to be installed are to meet the basic functional and physical independence between modules. Typically, parts with strong interrelationships are divided into the same module. Table 3 gives the module-to-module function and physical function independent interactivity

values. The interaction factor $I_{p(i,j)}$ indicates the interrelationship between parts i,j to be installed. The value of $I_{p(i,j)}$ is in the range of 0-1, and a larger value means a stronger interrelationship.

Table 3: Relationship description

No.	Relationship type	Interaction factor	Relationship description
1	Extremely strong	1	Non-splittable
2	intimacy	0.8	Strongly linked and related parts
3	Medium	0.6	Have some interaction and relevance
4	General	0.4	Loose relationship and weak interactivity
5	Weak	0.2	The relationship between parts is largely independent
6	None	0	No connection between parts

3.6 Model construction for module division of parts to be assembled

In order to facilitate the combination of the above four principles with the module classification method, this paper constructs a matrix based on the analytic hierarchy process[32] (AHP) and uses the fuzzy cluster analysis method for the module classification of components.

The steps for constructing the fuzzy similarity matrix are as follows:

1) integrate four modular design factors for the decommissioned machine parts to be assembled;
2) analyse the relative importance of each criterion using AHP;
3) assign weights in turn;
4) establish the fuzzy similarity matrix R for the parts to be assembled.

Suppose the library of parts to be assembled contains n basic modules, where $x_{(i,j)}$ is the similarity interaction value between basic modules i,j, which means the sum of the product of the weights of each feature criterion and its interaction factor[9]:

$$x_{(i,j)} = w_e I_{e(i,j)} + w_a I_{a(i,j)} + w_c I_{c(i,j)} + w_p I_{p(i,j)} \tag{14}$$

where $w_e \geqslant 0$, $w_a \geqslant 0$, $w_c \geqslant 0$, $w_p \geqslant 0$, and $w_e + w_a + w_c + w_p = 1$. The larger value of $x_{(i,j)}$ indicates a better interaction between the modules of the parts to be assembled.

Constructing a comprehensive correlation matrix R for the parts to be fitted:

$$R = \begin{bmatrix} x_{(1,1)} & \cdots & x_{(1,n)} \\ \vdots & \ddots & \vdots \\ x_{(n,1)} & \cdots & x_{(n,n)} \end{bmatrix}$$

The fuzzy similarity matrix R_M is constructed according to the maximum-minimum method[33].

$$R_M = \begin{bmatrix} r_{(1,1)} & \cdots & r_{(1,n)} \\ \vdots & \ddots & \vdots \\ r_{(n,1)} & \cdots & r_{(n,n)} \end{bmatrix}$$

where $r_{(i,j)} = \dfrac{\sum\limits_{k=1}^{n} \min(x_{(i,k)}, x_{(j,k)})}{\sum\limits_{k=1}^{n} \max(x_{(i,k)}, x_{(j,k)})}$ 。

The matrix R_M has two properties:

1) Self-reflexivity: for any $i = j$, there is $r_{(i,j)} = 1$;

2) Symmetry: for any $i \neq j$, there is $r_{(i,j)} = r_{(j,i)}$.

After generating the module partitioning scheme, the module partitioning is performed using the transitive closure method[34]. First of all, the transitive closure method of clustering needs to find a fuzzy equivalence matrix R_M^k of R_M. The passing closure of R_M^k is $t(R_M^k)$, that is, $t(R_M^k) = R_M^k$. After the equivalence matrix R_M^k is derived, a threshold $\lambda (\lambda \in [0,1])$ is set to derive the λ-intercept matrix, and finally the dynamic clustering map of each part to be installed is obtained. The closer the value of λ is to 1, the stronger the correlation between the parts but the higher the number of modules. So an appropriate λ value should be selected to obtain a reasonable module division scheme.

4 CASE STUDY

To verify the validity of the proposed theory and method, this paper takes the library of parts to be assembled on a CW61100 lathe inside a remanufacturing plant as the research object, and divides it into reasonable modules. Table 4 shows the list of some parts in the parts-to-be-assembled library. Figure 2 shows the internal diagram of the remanufactured spindle box of a CW61100 lathe.

Figure 2: Internal diagram of remanufactured spindle box

Table 4: Partial parts list

Code	Parts name	Parts type	Code	Parts name	Parts type	Code	Parts name	Parts type
1	Bed	Reused	7	Chuck	Reused	13	Lubrication system	New
2	Bed guide	Remanu-factured	8	Knife tower	New	14	Chip conveyor	New
3	Spindle box	Remanu-factured	9	Numerical control unit	New	15	Cooling unit	Reused
4	Small skate guide	Remanu-factured	10	Wire rod support assembly	Reused	16	Oil pump	New
5	Tailstock	Remanu-factured	11	Sliding seat	Reused	17	Nylon drag chain	New
6	Wire rod	Reused	12	Hydraulic system	Reused	18	Servo motor	Reused

4.1 Build a comprehensive correlation matrix of remanufactured parts to be assembled

This paper uses AHP to analyse the relative importance of the module classification criteria for remanufactured parts to be assembled and to find the weights.

First, the above four classification principles are scored two-by-two according to the expert evaluation method to obtain the comparison matrix A:

$$A = \begin{bmatrix} 1 & 1 & 2 & 1 \\ 1 & 1 & 1 & 1/2 \\ 1/2 & 1 & 1 & 1/2 \\ 1 & 2 & 2 & 1 \end{bmatrix}$$

Next, Matlab software is applied to solve the weights. The following results are obtained:

$$w_1 = 0.29 \qquad w_2 = 0.20 \qquad w_3 = 0.17 \qquad w_4 = 0.34$$

Then, take the example of part 2 (bed guide) and part 4 (small skate guide) to be assembled. The values of their correlation factors are calculated as follows:

Part 2 to be assembled is a remanufactured part with a total cost of ¥1818.5, and part 4 is also a remanufactured part with a total cost of ¥585.05. According to equation (5), the economic correlation factor of the two can be obtained as $I_{e(2,4)} = \dfrac{\min(C_{E2}, C_{E4})}{\max(C_{E2}, C_{E4})} = 0.32$

Parts 2 and 4 are remanufactured, so the accuracy level of both is the secondary accuracy. According to equation (6), the accuracy correlation factor of both can be obtained as $I_{a(2,4)} = \dfrac{\min(AC_2, AC_4)}{\max(AC_2, AC_4)} = 1$

The CO_2 emission factor of electricity consumption is 1.0069 $kgCO_2$/Kw•h, and the warming potential of GWP_{CO_2} is 1[35]. According to the research data, the carbon emission of part 2 is 513.0024 kg, and part 4 is 166.214 kg. According to equation (13), the carbon emission correlation factor of both can be obtained as $I_{c(2,4)} = \dfrac{\min(CE_2, CE_4)}{\max(CE_2, CE_4)} = 0.32$

It is known that the bed guide acts on the machine bed and the small skate guide acts on the tool holder; so the functional and physical interactivity factor is 0.6.

According to equation (14), the similarity interaction values between parts 2 and 4 can be obtained as $x_{(2,4)} = 0.29 \times 0.32 + 0.20 \times 1 + 0.17 \times 0.32 + 0.34 \times 0.6 = 0.55$

Similarly, based on the information of any two other basic modules, the similarity interaction values between any two basic modules can be obtained according to equation (14) to construct the comprehensive association matrix R of the parts to be assembled.

$$R = \begin{bmatrix} 1 & 0.74 & 0.56 & 0.69 & 0.72 & 0.60 & 0.49 & 0.33 & .. & 0.54 \\ 0.74 & 1 & 0.74 & 0.55 & 0.76 & 0.45 & 0.35 & 0.46 & .. & 0.36 \\ 0.56 & 0.74 & 1 & 0.51 & 0.65 & 0.50 & 0.50 & 0.43 & .. & 0.45 \\ 0.69 & 0.55 & 0.51 & 1 & 0.53 & 0.69 & 0.52 & 0.44 & .. & 0.56 \\ 0.72 & 0.76 & 0.65 & 0.53 & 1 & 0.50 & 0.38 & 0.41 & .. & 0.39 \\ 0.60 & 0.45 & 0.50 & 0.69 & 0.50 & 1 & 0.57 & 0.29 & .. & 0.60 \\ 0.49 & 0.35 & 0.50 & 0.52 & 0.38 & 0.57 & 1 & 0.24 & .. & 0.73 \\ 0.33 & 0.46 & 0.43 & 0.44 & 0.41 & 0.29 & 0.24 & 1 & .. & 0.39 \\ 0.30 & 0.42 & 0.46 & 0.30 & 0.38 & 0.28 & 0.23 & 0.77 & .. & 0.45 \\ . & . & . & . & . & . & . & . & .. & .. \\ . & . & . & . & . & . & . & . & .. & .. \\ 0.54 & 0.36 & 0.45 & 0.56 & 0.39 & 0.60 & 0.73 & 0.39 & .. & 1 \end{bmatrix}$$

4.2   Fuzzy cluster analysis method to find out the module division scheme

Based on the matrix R, we can obtain a tree diagram of the relationships between the parts to be fitted, as shown in Figure 3. The nodes directly connected in the diagram are closely related, while the nodes with multiple connections are less similar.
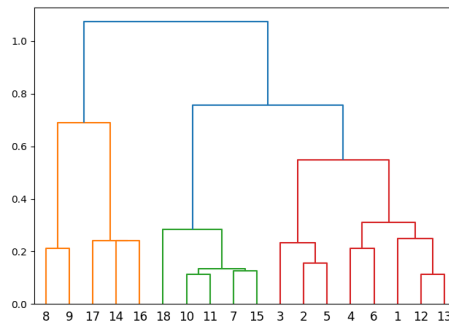
Figure 3: Tree view

Fuzzy clustering analysis of parts to be assembled using the transitive closure method:

At $\lambda=0.79$, the remanufactured parts to be assembled can be divided into three modules: M_1={1 2 3 4 5 6 7 10 11 12 13 15 18}，M_2={8 9}，M_3={14 16 17}。

At $\lambda=0.83$, the remanufactured parts to be assembled can be divided into five modules: M_1={1 4 6 12 13}，M_2={2 3 5}，M_3={7 10 11 15 18}，M_4={8 9}，M_5={14 16 17}。

At $\lambda=0.85$, the remanufactured parts to be assembled can be divided into eight modules: M_1={1 12 13} , M_2={2 3 5}，M_3={4 6}，M_4={7 10 11 15 18}，M_5={8 9}，M_6={14}，M_7={16}，M_8={17}。

This study uses the F-statistic[36] to find the optimal classification. Finally, this study determines the module division scheme at $\lambda=0.83$, which is divided into five modules. At this point, the module division scheme is more reasonable.

5   CONCLUSION

This paper uses a library of parts to be assembled in a remanufacturing plant as the object of study and the similarity interaction values between two parts to be assembled are calculated from the principles of economy, accuracy, environmental friendliness, and functional and physical interaction. The weights of the above four principles are calculated by applying the analytic hierarchy process, and then a comprehensive correlation matrix of the components to be assembled is constructed. On this basis, the fuzzy similarity matrix is calculated by using the maximum-minimum method. Next, the fuzzy similarity matrix is analysed by using a Python program to obtain different module division schemes with different thresholds. Finally, a reasonable module division scheme is selected. In the study case, the model is validated by the case of a remanufacturing plant with a library of parts to be installed on CW61100 lathes. This paper determines the weight coefficients of four principles, based on the actual situation of this plant. After obtaining the comprehensive correlation matrix, this research obtains the final module division scheme. The results show that the module partitioning model is feasible in the remanufactured parts-to-be-assembled library.

6   REFERENCES

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