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A Fuzzy Decision Support Approach for Modularization Scheme Selection of Product-Service Offerings

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ABSTRACT Many manufacturers today are striving to offer high value-added product-service offerings (PSO) due to increasing competitions and environmental concerns. Modularization of PSO can improve design efficiency and quickly response to customer's personalized requirements. However, research has rarely been conducted on the PSO modularization schemes evaluation which is critical to the success of the whole modularization. There are also no proper evaluation criteria for such heterogeneous form of hybrid solution. Therefore, in order to select reasonable modularization scheme of PSO, an approach based on fuzzy TOPSIS with integrated weights is proposed in this paper. Integration of subjective weight and objective weight helps to avoid underestimating or overestimating weigh of evaluation criteria, while the fuzzy TOPSIS approach provides a structure of multi-criteria decision-making (MCDM) under uncertain environment. A case study of compressor rotor service is used to validate the feasibility and effectiveness of the proposed method.

INDEX TERMS Fuzzy TOPSIS, integrated weight, modularization, multi-criteria decision making, product-service offerings (PSO).

I. INTRODUCTION

With the increasing competition [1], [2] and environmental pressures [3], many manufacturers are striving to re-position themselves as service providers by offering high value-added services [4]–[7]. They provide Product-Service Offerings (PSO) with high value, e.g., technology support, MRO (Maintenance, Repair & Operations), retrofitting, remanufacturing, recycling, and energy saving, etc [8]. PSO can help to increase the utility delivered by manufacturing company [9] and the product life [10], [11]. In order to quickly respond to customer demand for personalized PSO, services providers can use some common PSO modules in the design process for flexible customization. The modularization is an effective approach to lower the innovation cost [12], to reduce the negative environment impact [13], [14], to manipulate the personalized needs and to enhance the positive effects at the different phases of product life cycle [15]–[17]. Modularization can help to share design resources, reduce design costs and shorten delivery time of PSO [18]. PSO modularization refers to gather service processes, service resources and other service elements into service modules with independent functions, standard interfaces, loose coupling and strong inner cohesions. These service modules can be reused in the PSO design process. One of the most important advantages of PSO modularization is that it can flexibly meet the new design changes by reorganizing the PSO elements in module without substantially affect the other modules.

However, the elements constituting the PSO include service resource, service processes and service objects, which makes the service content and structure more complex and flexible. PSO modularization can usually obtain different modularization schemes due to different combination ways of service components. Modularization can lower the cost and reduce the lead time of product development. Due to the complex nature of PSO, PSO alternatives are often acquired with modularization. However, fewer previous studies focus on the PSO modularization schemes assessment. PSO modularization scheme decision making is critical to later workload of module configuration and service delivery.

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Therefore, taking into account the variety of the PSO modularization scheme, it is necessary to evaluate modularization schemes under certain criteria, and choose the most reasonable modularization scheme for the PSO configuration. Partitioning module is the basis of product modularization. The rationality of the module partition directly affects the function, performance, development time, cost, general degree of module, convenience of maintenance and so on. However, compared with modularization scheme of traditional product, PSO modularization scheme contains many intangible services elements (e.g. service processes and tasks) and tangible product elements (such as fault diagnosis devices, spare parts), which makes it to be a heterogeneous form of hybrid solution. In addition, evaluation of such heterogeneous modularization scheme is ambiguous and subjective. In order to keep the accuracy of the modularization scheme evaluation, and reduce undervaluation or overvaluation of criteria weights, it needs to not only consider the expertise knowledge, but also take advantage of the objective information in decision making process. Considering the situations which are mentioned above, this paper fills the research gap from both theoretical and empirical research perspective. Not only the objective, but also the subjective information is utilized when the decision is made. Besides, a novel integrated weighting approach is conducted to reduce decision makers' deflective influence. Moreover, the accuracy of the evaluation is delicately kept by taking comprehensive services elements and product elements into consideration.

The rest of this research is arranged as follows. Literature review is conducted in Section 2. The proposed method for PSO modularization evaluation under vague environment is presented in Section 3. In Section 4, a case study of modularization evaluation of compressor rotor service is used to validate the feasibility and effectiveness of the proposed method. Conclusions are summarized in Section 5.

II. LITERATURE REVIEW

Some previous studies begin to explore the domain modularization of product service offerings. Yin *et al.* [19] consider that modularization can help to realize component commonality and provide a various products with lower cost. Geum *et al.* [20] propose a modularization framework of service based on the structure of HoQ (House of Quality). Song and Sakao [21] propose a customization framework based on the modularization for the sustainable product service offerings. Aurich *et al.* [22] provide a process of modular design of product service offerings which links with the corresponding processes of product design. Wang *et al.* [23] provide a modular development framework and process for product-service system, which includes functional modularization, product modularization, and service modularization. Peters and Leimeiste [24] develop a modularization method which is suitable for customer-centric and tailored telemedicine services. Song *et al.* [18] propose a modualrization approach for product service offerings based on modified service blueprint and fuzzy graph. Umeda *et al.* [3] evaluate the modular structure by assuming that each module goes through different product lifecycle stages designated by the lifecycle scenario, such as retrofitting, reusing, and recycling, etc. Fixson [25] assesses product architecture cost by investigating product life cycles, allocation rules, and cost models. Yigit and Allahverd [26] propose an approach to optimize and select the modules of products in a RMS (Reconfigurable Manufacturing System). To obtain the most reasonable modularization scheme, Wang *et al.* [27] use fuzzy comprehensive evaluation method into product modularization decision makings. Zhao *et al.* [28] introduce "information entropy" concept to evaluate the different modularization schemes, then choose the best modularization scheme. Teng *et al.* [29] utilize the fuzzy clustering method to get some modularization schemes for shipbuilding, then they use a fuzzy comprehensive evaluation method to select a relatively reasonable one. Wang and Chen [30] propose a fuzzy MCDM based QFD to optimize the optimal selection of module mix. Zha *et al.* [31] propose a fuzzy clustering and ranking approach to evaluate and select modular product architecture for customization. Kim and Moon [32] provide a Markov Cluster Algorithm-based approach to identify eco-modular product architecture and evaluate the architecture modularity with different metrics from the viewpoint of product recovery.

Although PSO modularization scheme are critical to the success of PSO configuration and customization, past researches mostly focus on product modularization decision making. Fewer studies have been conducted on the assessment and selection of PSO modularization schemes. PSO modularization scheme is a heterogeneous solution of tangible product and intangible service, many subjective and qualitative indicators are used to assess the modularization results (e.g. service module flexibility, coupling degree of module), so PSO modularization decision making contains much fuzziness. In addition, the weights of evaluation criteria are often determined subjectively which depends much on experts' experience and knowledge. It considers less about the inherent information of decision data. In this respect, weights of evaluation criteria will easily be underestimated or overestimated which leads to inaccurate results of PSO modularization scheme.

III. THE PROPOSED METHOD FOR PSO MODULARIZATION SCHEME EVALUATION

The proposed decision method for PSO modularization includes three stages (see figure 1): first, the evaluation criteria of PSO modularization scheme are determined in the first stage. Then, in the second stage, subjective criteria weights and objective criteria weights of PSO modularization scheme are calculated respectively. Then, the subjective weights and objective weights are integrated to get the final composited criteria weights of PSO modularization. Finally, closeness coefficient for each modularization scheme of PSO is calculated based on a fuzzy TOPSIS in the third stage. The best modularization scheme of PSO can be selected based on value of closeness coefficient in this stage.

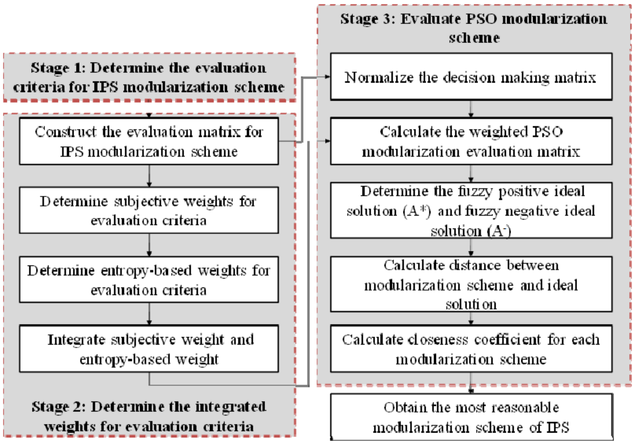

FIGURE 1. The PSO modularization decision making method.

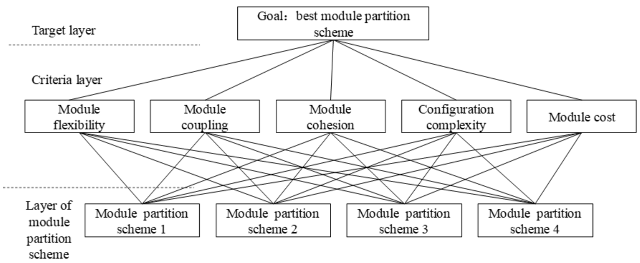

FIGURE 2. Evaluation hierarchy of PSO modularization scheme.

The proposed method can make full use of the subjective experts' knowledge and the objective intrinsic information based on Shannon's entropy concept [33].

A. STAGE 1: EVALUATION CRITERIA DETERMINATION FOR PSO MODULARIZATION SCHEME

Considering the PSO module definition and characteristics presented in Song *et al.* [18], we mainly evaluate the modularization scheme from the perspective of module flexibility, module coupling, module cohesion, configuration complexity and module cost, as is shown in Figure 2.

1) PSO MODULE FLEXIBILITY

PSO module flexibility refers to meet different types of customer requirements with combination of modules in PSO modularization scheme. PSO modularization scheme with high flexibility can meet customer needs through a simple combination of module. On the contrary, PSO modularization scheme with lower flexibility are often unable to respond to quickly customer requirement changes, because service providers have to re-design the PSO module which will lead to design cost increasing. The number of service components contained in the PSO module also affect the module flexibility. Once the total amount of service components is given, more types of services can be configured if there are less interrelations between service components, then PSO modularization scheme has higher flexibility; on the contrast, if there are more interrelations between service components, less types of services can be configured, because changing one module will lead to changes of other related service components, then PSO modularization scheme has lower flexibility.

2) PSO MODULE COUPLING

PSO module coupling is an indicator to measure module independence. It indicates the degree of interdependence between the different PSO modules. Generally, service designers expect that less interdependence relationships exist between PSO modules, because less interdependence relationships means to the stronger independence between the PSO modules, and interaction complexity between modules are lower. Thus, it can easily perform the service function independently. If interdependence existing between service components is strong, but interdependence between the PSO modules is weak, then those PSO modules are considered to be loosely coupled.

3) PSO MODULE COHESION

PSO module cohesion denotes the interconnection tightness of the service components in PSO module. Service components form a coherent module through the interactions between resources, information, and personnel, etc. Module stability and efficiency are higher when the internal service components are highly cohesive. If internal interdependence between service component of module with high cohesion is strong, it is apparent for PSO module to perform certain function as a whole, so the module efficiency is relatively higher. In addition, if the PSO module cohesion are stronger, consistency of service function and performance can then be maintained, that is, the stability of PSO module can be ensured.

4) MODULE CONFIGURATION COMPLEXITY

The smaller the granularity of PSO modularization, the more modules will be obtained. More modules will lead to increasing of interfaces and protocols between modules, which will affect the time and accuracy of module configuration. In this respect, PSO module configuration is increasingly complex, and it requires more resources, protocols, and capability to deal with complex relationships between these interfaces.

5) PSO MODULE COST

In the process of PSO modularization, it is necessary to consider reducing design cost, configuration cost and delivery cost of module in advance. In this respect, the components with higher costs and added value should be separated in the partition process to reduce the loss of cost caused by mistakes.

B. STAGE 2: CRITERIA WEIGHT DETERMINATION FOR PSO MODULARIZATION SCHEME

1) EVALUATION MATRIX CONSTRUCTION FOR PSO MODULARIZATION SCHEME

m modularization schemes MPS_i ($i = 1, 2 \ldots, m$) are assessed with n evaluation criteria. Each modularization

TABLE 1. Linguistic terms for the evaluation scores of modularization schemes.

Linguistic terms	Fuzzy numbers
Very poor (VP)	(0, 0, 1)
Poor (P)	(0,1, 3)
Medium poor (MP)	(1, 3,5)
Fair (F)	(3, 5,7)
Medium good (MG)	(5, 7, 9)
Good (G)	(7, 9, 10)
Very good (VG)	(9, 10, 10)

scheme MPS_i can be evaluated with the linguistic terms (see Table 1) under the jth criterion $C_j (j = 1, 2, \ldots, n)$. If there are k experts, the evaluation scores of MPS_i under the criterion C_j can be obtained:

$$\tilde{y}_{ij} = \frac{1}{k}[\tilde{y}_{ij}^{1} + \tilde{y}_{ij}^{2} + \ldots + y_{ij}^{k}] \tag{1}$$

where $\tilde{y}_{ij}^{k}$ indicates the evaluation score of the kth decision maker for the ith modularization scheme under the jth criterion C_j. The modularization scheme evaluation can be considered as a problem of fuzzy MCDM (Multiple Criteria Decision Making), which can be represented with a matrix M.

$$M = \begin{matrix} MPS_1 \\ MPS_2 \\ \vdots \\ MPS_m \end{matrix} \begin{bmatrix} \tilde{y}_{11} & \tilde{y}_{12} & \cdots & \tilde{y}_{1n} \\ \tilde{y}_{21} & \tilde{y}_{22} & \cdots & \tilde{y}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{y}_{m1} & \tilde{y}_{m2} & \cdots & \tilde{y}_{mn} \end{bmatrix} \tag{2}$$

$$W = (w_1, w_2, \ldots, w_j, \ldots, w_n) \tag{3}$$

where W indicates the weights of the evaluation criteria.

According to the Table 1, all the linguistic variables in the matrix M can be transformed into fuzzy numbers. And then, to convert the fuzzy number into crisp number, the method of graded mean integration is used. For any fuzzy number $\tilde{N}$ (a, b, c), the graded mean integration can be conducted as follows:

$$\text{Crisp}\left(\tilde{N}\right) = \frac{a + 4b + c}{6} \tag{4}$$

where $\text{Crisp}\left(\tilde{N}\right)$ indicates the crisp form of the fuzzy number $\tilde{N}$.

2) INTEGRATED WEIGHTS DETERMINATION FOR EVALUATION CRITERIA

a: STEP 1: DETERMINE SUBJECTIVE WEIGHTS FOR EVALUATION CRITERIA

The linguistic terms of the criteria importance for the PSO modularization scheme is provided in Table 2. According to the Table 2, linguistic judgments for evaluation criteria of each modularization scheme are calculated to get the subjective criterion weight. Different decision makers' linguistic judgments on each modularization scheme can be obtained as follows:

$$\tilde{W_{sj}} = \frac{1}{n}\left(\sum_{j=1}^{n} w_j^k\right) \tag{5}$$

TABLE 2. Linguistic terms of the criteria weights.

Linguistic terms	Fuzzy numbers
Very low (VL)	(0, 0, 0.1)
Low (L)	(0, 0.1, 0.3)
Medium low (ML)	(0.1, 0.3, 0.5)
Medium (M)	(0.3, 0.5,0.7)
Medium important (MH)	(0.5, 0.7,0. 9)
Important (H)	(0.7, 0.9, 1)
Very important (VH)	(0.9, 1, 1)

where w_j^k (j = 1, 2,…, n) is the kth decision maker's judgments on the weight of the jth criterion of PSO modularization scheme. After that, the subjective weight in form of fuzzy number can be transformed into crisp form w_{sj} according to the Eq. (4).

b: STEP 2: DETERMINE ENTROPY-BASED WEIGHTS FOR EVALUATION CRITERIA

To fully reflect intrinsic decision making information, objective weighting method based on Shannon's entropy concept is utilized in this section. The entropy-based objective weighting approach considers that weight of a criterion is related with the its conveyed information relative to the set of evaluations of PSO modularization schemes. That is, if a greater dispersion exists in the evaluations of the modularization schemes under a certain criterion, the criterion is considered to be more important than other criteria. The calculation steps of entropy-based weighting approach can be conducted as follows:

Firstly, according to the Eq. (4), the fuzzy numbers in matrix M can be converted into crisp value, and then the matrix with crisp numbers can be normalized to acquire the projection value P_{ij} of each modularization scheme.

$$P_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}} \tag{6}$$

where x_{ij} represents the crisp assessment of modularization schemes under the jth criterion.

Secondly, calculate the 'En_j' (entropy value) for different criteria:

$$En_j = -\beta \sum_j P_{ij} \ln P_{ij} \tag{7}$$

where $\beta = {}^{1}/_{\ln m}$.

Thirdly, the dispersion (DP_j) of the conveyed information by the criterion C_j is calculated with the formula (8).

$$DP_j = 1 - En_j \tag{8}$$

where DP_j is the contrast intensity of the criterion C_j. The greater the value of 'DP_j', the greater the importance of the criterion C_j.

After that, the objective weight (w_{oj}) of each evaluation criterion can be obtained as follows:

$$w_{oj} = \frac{DP_j}{\sum_{k=1}^{n} DP_k} \tag{9}$$

c: STEP 3: INTEGRATE SUBJECTIVE WEIGHT AND ENTROPY-BASED WEIGHT

To get comprehensive weight w_j for each evaluation criterion, both subjective weights w_{sj} and objective weights w_{oj} are integrated as follows:

$$w_j = \frac{w_{sj\times}w_{oj}}{\sum_{j=1}^{n} w_{sj\times}w_{oj}}, \quad j = 1, 2, \ldots, n \tag{10}$$

C. STAGE 3: EVALUATION OF PSO MODULARIZATION SCHEME

1) STEP 1: NORMALIZE THE DECISION MAKING MATRIX

In order to preserve all the criteria values in the decision making matrix in a comparable scale, the method of linear scale conversion is conducted as follows:

$$\tilde{r}_{ij} = \left(\frac{d_{ij}}{f_j^*}, \frac{e_{ij}}{f_j^*}, \frac{f_{ij}}{f_j^*}\right), \quad \text{if the criterion Ci is benefit criterion;} \tag{11}$$

$$\tilde{r}_{ij} = \left(\frac{d_j^-}{f_{ij}}, \frac{d_j^-}{e_{ij}}, \frac{d_j^-}{d_{ij}}\right), \quad \text{if the criterion Ci is cost criterion.} \tag{12}$$

where $f_j^* = f_{ij}$, if the criterion C_i is benefit criterion; $d_j^- = d_{ij}$, if the criterion C_i is cost criterion.

2) STEP 2: CALCULATE THE WEIGHTED PSO MODULARIZATION EVALUATION MATRIX

The normalized PSO modularization evaluation matrix represented by $\tilde{Q}$ can be obtained as follows:

$$\tilde{Q} = [\tilde{s}_{ij}]_{m\times n} \tag{13}$$

Then, the weighted normalized PSO modularization evaluation matrix $\tilde{U}$ is built as follows:

$$\tilde{U} = [\tilde{u}_{ij}]_{m\times n}, \tag{14}$$

$$\tilde{u}_{ij} = \tilde{s}_{ij}(\cdot)w_j \tag{15}$$

3) STEP 3: DETERMINE THE A* AND A⁻

Then, the fuzzy positive ideal solution A^* and fuzzy negative ideal solution A^- are defined as follows.

$$A^* = [(1; 1; 1); (1; 1; 1); \ldots; (1; 1; 1)]_{1\times n} \tag{16}$$

$$A^- = [(0; 0; 0); (0; 0; 0); \ldots; (0; 0; 0)]_{1\times n} \tag{17}$$

4) STEP 4: CALCULATE THE DISTANCE BETWEEN EACH MODULARIZATION SCHEME AND IDEAL SOLUTION

The distance between each modularization scheme and ideal solutions (the fuzzy positive ideal solution A^* and fuzzy negative ideal solution A^-) can be obtained as follows.

$$d_i^* = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^*), \tag{18}$$

$$d_i^- = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^-), \tag{19}$$

For any two triangular fuzzy numbers, $\tilde{\alpha} = (\alpha_1, \alpha_2, \alpha_3)$ and $\tilde{\gamma} = (\gamma_1, \gamma_2, \gamma)$, the distance $(d(\tilde{\alpha}, \tilde{\gamma}))$ between the fuzzy number $\tilde{\alpha}$ and the fuzzy number $\tilde{\gamma}$ can be obtained as follows:

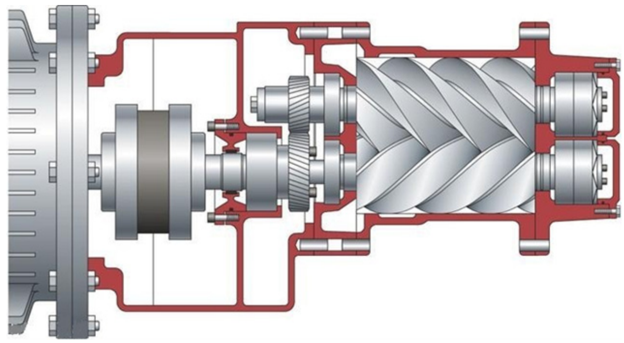

FIGURE 3. Vertical view of compressor rotor.

$$d(\tilde{\alpha}, \tilde{\gamma}) = \sqrt{\frac{1}{3}[(\alpha_1 - \gamma_1)^2 + (\alpha_2 - \gamma_2)^2 + (\alpha_3 - \gamma_3)^2]} \tag{20}$$

5) STEP 5: DETERMINE CC_i (CLOSENESS COEFFICIENT) OF MODULARIZATION SCHEME

The $\boldsymbol{CC_i}$ of each PSO modularization scheme is obtained as follows.

$$cc_i = \frac{d_i^-}{d_i^* + d_i^-} \tag{21}$$

The closer to the fuzzy positive ideal solution A^* and farther from the fuzzy negative ideal solution A^- the ith modularization scheme MPS_i is, the more the closeness coefficient CC_i of MPS_i approaches to 1. Thus, the designers can select the most reasonable modularization scheme in the light of the CC_i.

IV. CASE STUDY

The proposed approach for PSO modularization scheme evaluation is put into an application of maintenance service design of compressor rotor in company I. Company I designs and manufactures screw air compressor and provides maintenance service to customers. Air compressor rotor is a critical part of the compressor (see Figure 3) which directly determines the compressor's operation condition. Maintenance service is necessary to keep the compressor in good operation condition. To reduce the service cost and increase the flexibility of the maintenance, the manufacturer decides to modularize the rotor maintenance services. With the PSO modularization method proposed in Song *et al.* [18], we can obtain four rotor maintenance modularization schemes, which is shown in Table 3. Here, we do not describe much about the specific PSO modularization process, because this case study mainly focuses on the evaluation of rotor maintenance modularization schemes. Interested readers are encouraged to read Song *et al.* [18] for more information of PSO module partition.

A. STAGE 1: EVALUATION CRITERIA DETERMINATION

According to section 3.1, we mainly evaluate the modularization scheme of rotor maintenance service from the

TABLE 3. Modularization scheme of compressor rotor maintenance.

Rotor maintenance modularization scheme		Modularization scheme 1	Modularization scheme 2	Modularization scheme 3	Modularization scheme 4
Service component distribution	Module 1	Rotor cleaning, Rotor adjustment & repair, Parts replacement, Disassembly &integration, Service engineer	Rotor cleaning, Rotor adjustment & repair, Parts replacement, Disassembly &integration, Service engineer, Spare parts, Dispatching, Dispatching system	Rotor cleaning, Rotor adjustment & repair, Parts replacement, Rotor status diagnosis, Disassembly &integration, Service engineer, Spare parts, Dispatching, Dispatching system	Rotor cleaning, Rotor adjustment & repair, Parts replacement, Rotor status diagnosis, Disassembly &integration, Service engineer, Spare parts, Dispatching, Intelligent diagnostic system, Dispatching system
	Module 2	Rotor status diagnosis	Rotor running, Condition monitoring, Condition monitoring device	Rotor running, Condition monitoring, Condition monitoring device	Rotor running, Condition monitoring, Condition monitoring device
	Module 3	Rotor running	Rotor status diagnosis	Intelligent diagnostic system	/
	Module 4	Condition monitoring	Intelligent diagnostic system	/	/
	Module 5	Spare parts	/	/	/
	Module 6	Condition monitoring device	/	/	/
	Module 7	Dispatching	/	/	/
	Module 8	Intelligent diagnostic system	/	/	/
	Module 9	Dispatching system	/	/	/

TABLE 4. Linguistic terms for evaluation criteria of each modularization scheme.

MPS_i	Module flexibility	Module coupling	Module cohesion	Configuration complexity	Module cost
MPS1	MG,MGG, G	VP, P, P,MP	F,MG ,F,MG	VG,VG, VG,VG	G, F , G,MG
MPS 2	G, G, MG, F	VG,VG,V G,G	MG,MG, G,G	MP,P, MP,MP	VP,P, P,MP
MPS 3	MG,MG, MG, F	MG,MG, F,F	G,G, MG,F	MP,F, F,MP	P,P, MP,MP
MPS 4	VP, P, P, MP	MG,MG, G,G	VP,VP, P,MP	P,MP, MP, P	VG,VG, MG,G

perspective of module flexibility, module coupling, module cohesion, configuration complexity and module cost.

B. STAGE 2: CRITERIA WEIGHT DETERMINATION FOR ROTOR SERVICE MODULARIZATION SCHEME

1) EVALUATION MATRIX CONSTRUCTION FOR MODULARIZATION SCHEME OF ROTOR SERVICE

Four experts are invited to utilize the linguistic terms in Table 1 to assess the modularization schemes of rotor maintenance under different evaluation criterion, and the expert evaluations are provided in Table 4. Meanwhile, the linguistic terms in Table 4 are used to build the fuzzy evaluation matrix in Table 5.

2) INTEGRATED WEIGHTS DETERMINATION FOR EVALUATION CRITERIA

The rotor maintenance service designers utilize the linguistic terms in Table 2 to evaluate the weights of the evaluation criteria for the rotor maintenance schemes, and the results

TABLE 5. The fuzzy evaluation matrix of modularization schemes.

MPS_i	Module flexibility	Module coupling	Module cohesion	Configuration complexity	Module cost
MPS1	(6,8,9.5)	(0.25,1,3)	(4,6,8)	(9,10,10)	(5.5,7.5,9)
MPS2	(5.5,7.5,9)	(8.5,9.75, 10)	(6,8,9.5)	(0.75,2.5, 4.5)	(0.25,1,3)
MPS3	(4.5,6.5,8.5)	(4,6,8)	(5.5,7.5,9)	(2,4,6)	(0.5,2,4)
MPS4	(0.25,1,3)	(6,8,9.5)	(0.25,1,2. 5)	(0.5,2,4)	(7.5,9,9.75)

TABLE 6. Linguistic terms for evaluation criteria weights of rotor maintenance schemes.

Evaluation criteria	Module flexibility	Module coupling	Module cohesion	Configuration complexity	Module cost
Linguistic variable	M,MH,M H,H	MH,M,M H,MH	M,M,M, MH	ML,M ,M,M	VH,H, MH,MH
Subjective weight w_{sj}	0.220	0.206	0.174	0.142	0.258

are listed in Table 6. The Eq. (4) is then used to transform the fuzzy importance of evaluation criteria into crisp numbers (see Table 6).

Then, the crisp evaluation matrix in Table 5 is normalized according to the Eq. (6). In this way, the projection value P_{ij} for each modularization scheme of rotor maintenance service is obtained (see Table 7).

According to the Eq. (7)-(9), 'Enj' and 'DPj' are determined to get the objective weight of evaluation criteria in Table 8.

TABLE 7. The projection value matrix for each modularization scheme of rotor maintenance service.

MPS_i	Module flexibility	Module coupling	Module cohesion	Configuration complexity	Module cost
MPS1	0.344	0.049	0.266	0.533	0.379
MPS 2	0.322	0.388	0.351	0.138	0.062
MPS 3	0.282	0.243	0.329	0.217	0.106
MPS 4	0.052	0.320	0.054	0.113	0.453

TABLE 8. The objective weights of evaluation criteria.

	Module flexibility	Module coupling	Module cohesion	Configuration complexity	Module cost
En_j	0.897	0.882	0.896	0.856	0.820
DP_j	0.103	0.118	0.104	0.144	0.180
w_{oj}	0.159	0.181	0.160	0.223	0.278

TABLE 9. The comprehensive weights and the fuzzy weighted normalized evaluation matrix.

	Module flexibility	Module coupling	…	Configuration complexity	Module cost
	W_1=0.172	W_2=0.183	…	W_4=0.156	W_5=0.353
MPS1	(0.108,0.145, 0.172)	(0.005,0.018,0.055)	…	(0.008,0.008,0.009)	(0.010,0.012,0.016)
MPS 2	(0.099,0.136, 0.163)	(0.156,0.179,0.183)	…	(0.017,0.031,0.104)	(0.029,0.088,0.353)
MPS 3	(0.081,0.118, 0.154)	(0.073,0.110,0.147)	…	(0.013,0.019,0.039)	(0.022,0.044,0.176)
MPS 4	(0.005,0.018, 0.054)	(0.110,0.147,0.174)	…	(0.019,0.039,0.156)	(0.009,0.010,0.012)

Comprehensive weight (see Table 9) for different evaluation criterion of rotor maintenance scheme is determined by integrating subjective weights in Table 6 and objective weights in Table 8.

C. STAGE 3: EVALUATION OF MODULARIZATION SCHEME FOR ROTOR MAINTENANCE SERVICE

The fuzzy weighted normalized evaluation matrix are determined in Table 9 with the Eq. (11)-Eq. (15). The fuzzy positive ideal solution A^* and fuzzy negative ideal solution A^- are set as follows:

$$A^* = [(1; 1; 1); (1; 1; 1); (1; 1; 1)],$$
$$A^- = [(0; 0; 0); (0; 0; 0); (0; 0; 0)].$$

The distance between each modularization scheme and ideal solutions (the fuzzy positive ideal solution A^* and fuzzy negative ideal solution A^-) can be obtained by using the Eq. (18)-Eq. (20), which is listed in Table 10. The $\boldsymbol{CC_i}$ of each rotor maintenance modularization scheme is obtained based on the Eq. (21) is also listed in Table 10.

Based on the $\boldsymbol{CC_i}$ in Table 10, the design managers can determine the most reasonable modularization scheme. Obviously, CC_2 is the largest, so the best modularization scheme of rotor maintenance service is MPS 2, that is, {Rotor cleaning, Rotor adjustment & repair, Parts replacement, Disassembly &integration, Service engineer, Spare parts, Dispatching, Dispatching system },{Rotor running, Condition monitoring, Condition monitoring device},{Rotor status diagnosis}, {Intelligent diagnostic system }.

TABLE 10. The d_i^*, d_i^-, CC_i and ranking order of each modularization scheme of rotor maintenance.

Modularization scheme	d_i^*	d_i^-	CC_i	Rank
MPS1	4.726	0.288	0.057	4
MPS 2	4.388	0.697	0.137	1
MPS 3	4.566	0.475	0.094	2
MPS 4	4.734	0.305	0.061	3

TABLE 11. Comparative analysis of the proposed approach versus Karim & Karmaker (2016) and Graham *et al* (2015).

Comparative perspective	Comparison results
Manipulating Uncertainty	Considering the fuzzy environment, fuzzy number set is utilized in the proposed method. However, the other two approaches choose to use crisp value to conduct decision-making process. In other words, the application range of the proposed method is wider.
Weights of Evaluation Criteria	The entropy-based method in our work combines the subjectivity and objectivity during the determination of the weights of evaluation criteria. While, the other two methods have only taken on aspect into account, which may lead to unexpected results.
GDM (Group Decision-Making) Support	Three approaches are all adequate to support GDM (Group Decision-Making) operations.
Computational Complexity	Karim & Karmaker (2016) enhance the TOPSIS by combining another MCDM methodology. On this basis, Graham et al. (2015) introduce entropy theory into the approach. In terms of computational complexity, Karim & Karmaker (2016) provide the fewest steps of the methodology, which requires the least time and endeavor to master.

D. DISCUSSION AND COMPARISONS

In the proposed evaluation method for PSO module scheme, both the subjective weights and entropy weights are integrated. On one hand, the subjective weights directly derived from the experts' linguistic evaluations can fully consider decision makers' experience and knowledge. On the other hand, the entropy weights are derived from the relative contrast intensities of attributes representing the average intrinsic information which is transmitted to the decision makers. If the information entropy of one criterion En_j is smaller, the weight

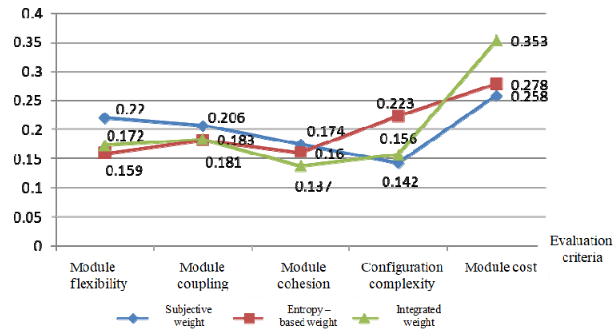

FIGURE 4. Vertical view of compressor rotor.

evaluation value variability of the criterion is greater, and the criterion will provide a larger amount of information. In this respect, it will play a greater role in the modularization scheme evaluation, and its weight will becomes higher. In the case study, the information entropy of criterion " Module cost " is 0.820 (En_5) which is the largest among the five information entropies ($En_1 = 0.897$, $En_2 = 0.882$, $En_3 = 0.896$, $En_4 = 0.856$, $En_5 = 0.820$). Therefore, the of criterion " Module cost " has the largest weight w_{o5} (0.278). The integrated weights of criteria for PSO modularization evaluation can reduce underestimation or overestimation of criteria. For the integrated weight of the criterion "Module flexibility" ($W_1 w_1 = 0.172$), the subjective weight ($w_{s1} = 0.22$) is relatively high, and the entropy-based weight ($w_{o1} = 0.159$) is relatively low (see Figure 4). The overestimation or underestimation of criterion weight will ultimately lead to inaccurate selection of PSO modularization scheme.

From a management point of view, the proposed method leads to two direct decision results. The one result is that decision-making time could be greatly reduced and expert resources would not be wasted during the decision-making process, because the model steps are refined and simplified as much as possible in order to be tractable for decision makers. The other one result is that reasonable modularization scheme of PSO can be selected with legitimate weights, in which way the design efficiency and quick response to customer's personalized requirements is ensured.

To validate the efficiency of our methodology, two relevant approaches (Karim & Karmaker, 2016; Graham et al., 2015) are introduced to make a comparison analysis. To sum up, the comparative result is shown in TABLE 11.

V. CONCLUSIONS

To select the most reasonable modularization scheme for PSO, the authors propose a fuzzy evaluation approach with integrated weights in this paper. General evaluation criteria for modularization scheme of PSO are firstly presented. Then, integrated weighting method is utilized to combine subjective weights and entropy-based weights to obtain the comprehensive weights of criteria, which helps to reduces the decision makers' bias and increase objectivity in the process of weight determination. After that, a method of weighted fuzzy TOPSIS is utilized to evaluate modularization schemes of PSO. The proposed fuzzy evaluation approach for PSO modularization is finally validated by a case study of modularization scheme evaluation of rotor maintenance, in which part, the criterion (Module cost) with the greatest information entropy ($En_5 = 0.820$) among the five criteria and it is obviously shown that it has the largest weight ($w_{o5} = 0.278$). In the case study, during the process of the evaluation, not only the accuracy is guaranteed, but the knowledge and experience of decision makers' are also reasonably estimated. According to the above, the proposed method has the following strengths:

The evaluation criteria for modularization scheme of PSO are initially proposed in this paper, which considers the features of PSO.

Linguistic terms are utilized to evaluate the PSO modularization scheme, which helps the designers to evaluate the modularization scheme reasonably and easily.

The entropy-based method reduces the subjectivity and enhances the objectivity of criteria weight determination for PSO modularization evaluation.

The integrated weighting approach can realistically reflect the importance of evaluation criteria of PSO modularization scheme by taking into account subjective and objective weights of criteria, and this helps to make PSO modularization scheme not being underestimated or overestimated.

Even though the proposed approach which based on fuzzy TOPSIS with integrated weights has distinct advantages dealing with PSO modularization scheme selection problems, there is still room left for future improvement. First, different fuzzy approaches can be introduced to compare with the proposed one like models based on hesitant fuzzy set theory, fuzzy VIKOR and fuzzy ELECTRE. Second, the interdependencies among the evaluation criteria of PSO modularization scheme will be considered in process of weight determination in the future research. Third, computer-aided tool can be tailored in further research aiming at high computation efficiency.

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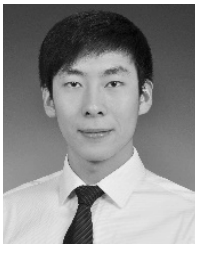

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