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Change impact analysis of complex product based on three-parameter interval grey number grey relational model

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Abstract: Change impact evaluation of complex product plays an important role in controlling change cost and improving change efficiency of engineering change enterprises. In order to improve the accuracy of change impact evaluation,this paper firstly expresses engineering changes based on multi-stage complex networks. Then, it constructs the evaluation index system of complex product engineering change impact. Next, based on the combination weighted three-parameter grey relational model, the engineering change impact of complex product is evaluated. Finally, a case analysis was carried out with the permanent magnet synchronous centrifugal compressor in a large permanent magnet synchronous centrifugal unit to verify the effectiveness of the proposed method.

Keywords:Complex product, Engineering change impact evaluation, Three-parameter interval grey number, Grey relational model

1. Introduction

There are increasingly fierce competition among complex product manufacturing enterprises in the rapidly changing market environment. In order to improve competitiveness and meet the changing needs of customers for engineering change, companies inevitably face more and more complex engineering changes. When engineering changes occur, many structures of complex products will be affected. The management of engineering change is roughly divided into four stages: engineering change application, engineering change process impact analysis and evaluation, engineering change decision and approval, and engineering change implementation. In these four stages, the analysis of the impact of engineering change can not only be used to determine the necessity of change implementation, but also provide guidance for the formulation of change decision and strategies. It is of great significance to control the cost of change and improve the efficiency of change, especially to consider the multi-stage impact when evaluating the impact of engineering change.

Due to the complexity of parts, disciplines and heterogeneous knowledge, and the difficulty of data acquisition, there is great opacity in the process of change impact evaluation. Therefore, this article improved three-parameter interval grey relational and applied to the evaluation of the impact of engineering changes.

In recent years, many scholars have studied the impact evaluation of engineering change. It

mainly includes the evaluation of change impact scope and the change impact degree. Based on the weighted network theory, (Cheng and Chu, 2012) proposed three variable indexes (degree variable, reachable variable and interval variable). And the degree variability is used to calculate the impact of direct change.Ahmad et al. (2013) studied a cross domain approach to decompose design and identify possible change propagation links, supplemented by an interactive tool to functions, components and detailed design process. Chen *et al*.(2015) proposed an assess the impact of changes. This method considered the information domain of requirements, object-oriented method, and described its components and related requirements by attributes and links, so as to model the integrated content of products and perform CIA tasks in variant product design. Maazoun *et al.*(2016) proposed an automatic method to analyze the evolution of feature change model, tracked their impact on SPL design, and provided a set of suggestions to ensure the consistency of the two models. Li *et al.*(2020) introduced multiple network model and application susceptibility infection susceptibility model into the impact evaluation of complex product engineering change propagation. Zheng *et al.*(2020) put forward the evaluation method of change propagation probability based on grey comprehensive relational analysis and the evaluation method of change propagation impact probability based on configuration change value analysis. (Li and Zhao, 2014) proposed an engineering change scheduling method which combined change propagation simulation with optimization algorithm in complex product development process. Ma *et al.*(2016) established an engineering change analysis model based on the design attribute network and defined the influence of change propagation on the intensity of change propagation through the quantification of change propagation influence factors. Zhang *et al.*(2017) proposed an impact model of engineering change delivery date based on capacity constraints. (Zhang and Yang, 2019) constructed a complex product design structure-task network evolution model under the influence of engineering changes, and analyzed the impact of changes on design tasks. Lian *et al.*(2017) studies the change rule of node state and the mechanism of change propagation in complex product design network. The improved cuckoo search algorithm is used to solve the design change propagation path, so as to comprehensively and accurately evaluate the impact of change on complex product design. (Guo, 2018) proposed a risk prediction method of engineering change propagation based on small world network. Li*et al.*(2020) established an engineering change risk propagation model based on load capacity.

Some of the existing studies have studied the change risk of change evaluation, and the change propagation. Then based on the multi-stage complex network model, this paper analyzes the multifaceted change propagation impact from the aspect of change propagation path. In addition, there are many parts in complex products and their relationship is complex. The relationship of each stage and parts is dynamic under the influence of engineering changes. Engineering change involves a series of activities such as product design or process, related documents, components or assembly, self-made or purchased parts, production process and even suppliers. The acquisition of engineering change data for complex products is more difficult and the data is poor, with greater ambiguity. Therefore, this paper adopts the three-parameter grey relational model based on BWM and Gini coefficient method to evaluate and analyze the impact of engineering change propagation.

Many scholars have studied three-parameter interval grey number decision model. For the multi-attribute decision-making problem, Hu *et al.*(2014) further expanded the greytarget decision model and gave a weighting method suitable for the ternary interval comprehensive target distance decision model. Li *et al.*(2015) proposed a decision-making method based on prospect theory for the multi-criteria decision-making problem where probability and criterion value are both three-parameter interval greynumbers. (Wang and Dang, 2015) proposed a dynamic multi-attribute decision-making method based on prospect theory for the dynamic multi-attribute decision-making problem where the attribute value of scheme is a three-parameter interval grey number. Yan *et al.*(2015) proposed a three-parameter interval grey number group decision method based on prospect theory, taking into account the influence of decision makers' satisfaction range of indexes and risk attitudes on group decision-making. Luo *et al.*(2016) proposed an attribute reduction method based on theta grey dominance relation for incomplete information system whose attribute evaluation value is three-parameter interval grey number. Li *et al.*(2019) proposed a multi-attribute decision-making method based on cosine similarity to solve the multi-attribute decision-making problem that the evaluation information is three-parameter interval grey number and the grey information set is not fully utilized. (Li and Zhang, 2020) proposed a grey target decision-making method considering the value information of the grey number in the three-parameter interval and the risk attitude of the decision maker.

There are also some researches on the index weight of grey relational model. (Sun and Huo, 2020) calculated the weight of attributes by improved entropy method, calculated the relative closeness of different schemes by TOPSIS method and grey relation algorithm, and sorted the alternatives by the relative closeness. (Yin and Ren, 2018) and Liu *et al.*(2020) respectively introduced entropy weight method into grey relation analysis to study the risk evaluation of tunnel, the representative volume evaluation of concrete and the comprehensive analysis of the influencing factors of gas outburst. Based on entropy TOPSIS grey relational method, Gu *et al.*(2020)and Guo *et al.*(2019) respectively studied the path selection of the evaluation of the opening level of coastal cities in China and the evaluation of the implementation effect of TCM standards. (Li and Zhu, 2019) studied the grey relational decision model based on AHP and DEA. Based on the sensitivity and grey relational degree, Zhou *et al.*(2017) studied the variable weight evaluation method of distribution network operation mode. For the determination of the weight of three parameter interval grey number index, according to different decision-making schemes, most scholars consider the weight of the index one sidedly, without considering the limitations of the method. In fact, every scheme is different in different situations. So the index weights of different schemes should be different. Therefore, this article combines the advantages of subjective and objective to comprehensively empower it and apply it to the evaluation of complex product engineering changes.

The engineering change process needs huge human, material and financial resources. If a predictive analysis of the possible impact scope can be made, manufacturing enterprise can avoid the waste of cost, and further accelerate the product development and production cycle. In this paper, the multi-stage complex network topology is firstly established for complex product

engineering change, then the engineering change impact evaluation system is established. Finally, the proved three-parameter interval grey relational model is used to evaluate the impact of engineering change. The framework is shown in the Figure 1.

2. Multi-stage complex network

Engineering changes occur in product design, process, manufacturing and other stages. When these changes occur, it is necessary to respond at any time to achieve real-time change design response, rather than follow a fixed process of production. All processes will be affected when the change occurs. It is very vital about how to effectively collect, organize and manage scattered product engineering change knowledge, and use existing domain knowledge to ensure the integrity of product assembly structure. As an important part of the re-generation of product design schemes after product changes, it is critical to timely feed back the engineering change information to the design department. This article builds a multi-stage complex network based on design libraries, knowledge bases, and case libraries.

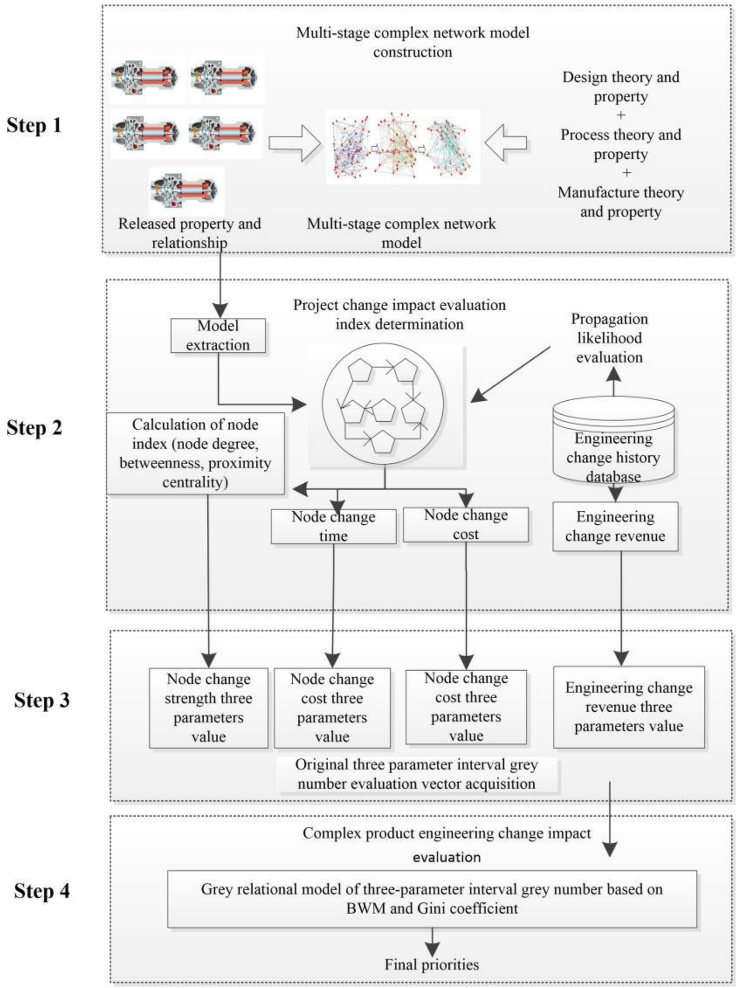


Fig.1 Framework of the proposed complex product engineering change impact evaluation method.

In design stage, structure and function of complex product are determined according to the market demand, which is the key to provide the guideline for the subsequent production and manufacturing. Therefore, the product design knowledge includes those specific parts and components, as well as a series of knowledge including the structure, function and behavior of the product. There are three sources of parts knowledge in product design stage. The function definition from the transformation of customer requirements is in the basic parts library. According to the requirements of the design structure, select knowledge from the basic parts library. Redesign the parts according to the subsequent changes. This knowledge network based on process must be able to accurately record the comprehensive information of each part for large and complex products, whether it is mass production or single piece small batch production. Knowledge network of complex product manufacturing stage is associated by the assembly material attribute information, supplier and quota information to each part in the assembly process information according to the requirements of parts purchasing and inventory management. In addition to material attribute information, self-made parts should also be associated with material quota, man hour quota, work center, tools, accessories, equipment and other information to form part manufacturing knowledge network. The multi-stage complex network construction process of complex product is shown in Figure 2.

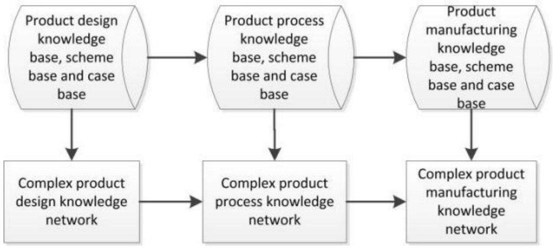


Fig.2 Multi-stage complex network of complex product

The single stage network is represented as: $G_k = (V, E_K, W_K)$ $V = (V_i, i = 1,2,...N)$. If there are connecting edges between parts knowledge, the $e^k_{k,j} = 1$, else, $e^k_{k,j} = 0$. When calculating the multi-stage network, the connected edges and edge weights of its indexes are added and processed. For the same connected edge, the weight value is $w_{i,j} = \sum_{\alpha}^{3} w^{\alpha}_{i,j}$. The schematic diagram of the multi-stage network is shown in Figure 3.(Taking the high speed permanent magnet synchronous variable frequency centrifugal high power chiller of G enterprise as an example.)

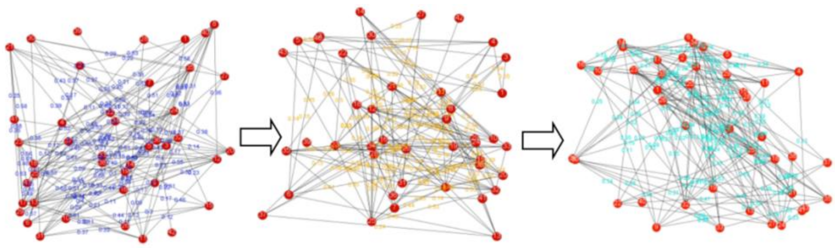


Fig.3 Multi-stage complex knowledge network

3. Construction of engineering change evaluation index

3.1 Engineering change propagation intensity evaluation

The propagation intensity of engineering change defined in this paper includes node proximity, edge betweenness and propagation probability.

Node proximity: Node proximity is the reciprocal of total distance from the node to all other nodes: $C_i = \frac{1}{\sum_{j=1}^{n} \beta_{ij}}$ Where β_{ij} is the number of edges in the shortest path from the start node i to the end node j , and n is the total number of nodes. Node proximity describes the degree a node is to the center of a network. The larger the value, the more importasnt the node is.

Edge betweenness:Edge betweenness is defined as the ratio of the number of paths passing through the edge to the total number of shortest paths in the network. Edge betweenness test is an important index to measure the role of connected edges in the whole network. The edge betweenness is expressed as: $G_{i,j} = \sum_h^N \sum_m^N \frac{L_{h,m(e_{i,j}^u)}}{g_{h,m}} / m = 1,2,...,N, h \neq m(h,m) \neq (i,j)]$.

Propagation probability of connected edges: $p_{i,j}$ is the probability of propagation from node i to node j . If node j doesn't belong to the next connected edge, the propagation probability is 0. It is easier to pass through this connecting edge when the propagation probability of the edge is greater. It can be expressed as: $P_{ij} = p(v_j|v_i) = \frac{p(v_i \cap v_j)}{p(v_i)} = \frac{p(v_j|v_i)p(v_j)}{p(v_i)} = \frac{p_{ji}p(v_j)}{p(v_i)}$

Then, the change propagation intensity can be expressed as: $I_{ij} = \begin{cases} \omega_1(1 - P_{ij}) + \omega_2 C_i + \omega_3 G_i, & p_{ij} \neq 0 \\ 0, p_{ij} = 0 \end{cases}$

3.2 Engineering change cost

Engineering changes of different parts will require different change costs. Changes in components can be mapped to changes in nodes in the network model (node addition and deletion). Therefore, we can evaluate the impact of customer demand change on complex product change by calculating the change cost of node change (node addition and deletion) in the network, the cost of node change in a network can be expressed as: $C_A = \sum_{i=1}^{N_A} c_{(v_i)}$ .Where, c_{v_i} is the change cost of node change, N_A is the total number of change nodes.

The cost details involved in the product production process include:(1) Material cost:It refers to the cost of product standard consumption, supporting raw materials, product accessories and various materials used for production or providing services. It mainly includes the purchase price, related taxes, freight, loading and unloading fees, insurance premiums and other costs that can be directly attributable to the acquisition of materials. (2) Labor cost:It refers to the remuneration and other expenses paid to employees which in order to obtain the services provided by employees. It mainly includes the salary, bonus, allowance, welfare, education fund and so on. (3) Manufacturing cost:It refers to energy consumption, manufacturing accessories, labor insurance,

office and fixed expenses. (4) Others: Some consumption including fuel cost, power cost, office cost and depreciation consumed by each production unit.

3.3 Engineering change time

In the process of engineering, change of different parts needs different change time. The node change time in a network can be expressed as: $T_A = \sum_{i=1}^{N_A} t_{(v_i)} + t_{(e_{i,j})}$.

Where, t_{v_i} is the change time of node change. N_A is the total number of change nodes.

3.4 Engineering change profit

It refers to the positive impact obtained in the change process, such as customer satisfaction, product performance improvement and so on. The engineering change profit can be expressed as: $I_A = \sum_{i=1}^{N_A} i_{(v_i)}$ .Where, t_{v_i} is the engineering change profit of node change. N_A is the total number of change nodes.

The impact evaluation indexes are as shown in Figure 4.

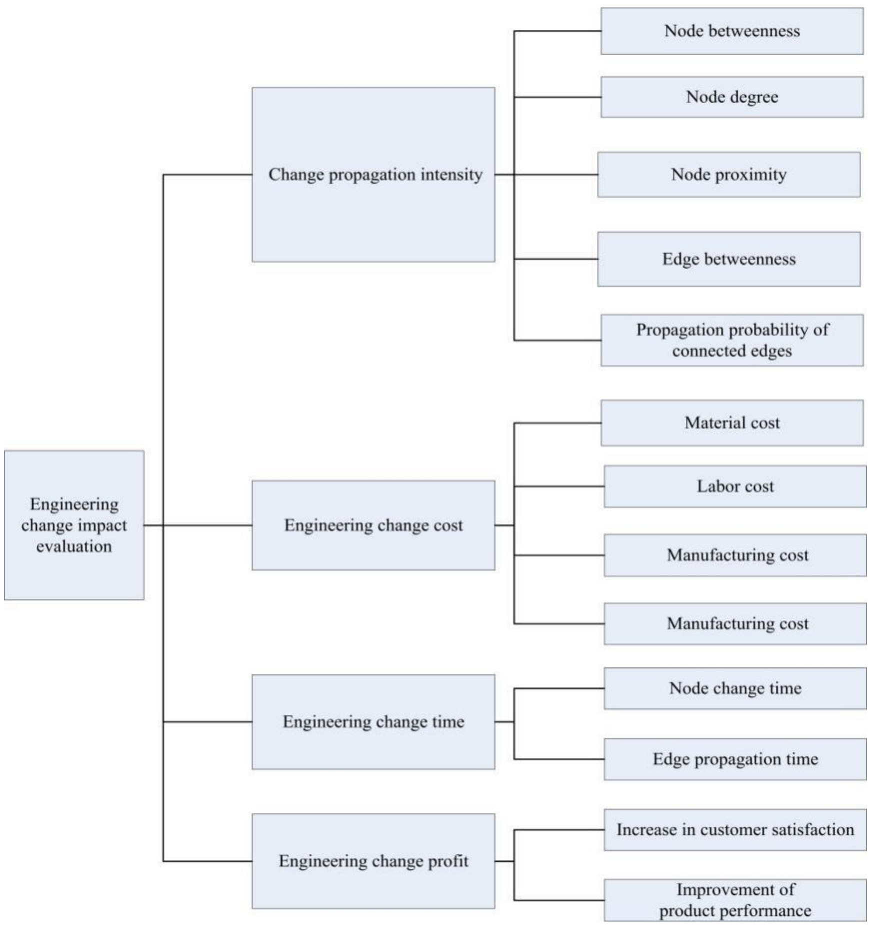


Fig.4 Evaluation indexes of engineering change impact

4. Grey relational evaluation model based on three-parameter interval grey number

4.1 Three-parameter interval grey number

From the definition of three-parameter interval grey number, it can be known that it refers to the interval grey number where the center of gravity point with the greatest possible value is known. It can be marked as $A(\otimes)=[\underline{a},\tilde{a},\bar{a}]$, where, $\underline{a}\le\tilde{a}\le\bar{a}$, $\underline{a}$ 、 $\bar{a}$ are the the upper and lower limits of the interval respectively. $\tilde{a}$ is called the "center of gravity" point.(Wang and Dang, 2019)

When two of the three parameters $\underline{a}$ 、 $\tilde{a}$ 、 $\bar{a}$ are the same, the three-parameter interval grey number degenerates to the interval grey number. When $\underline{a}=\tilde{a}=\bar{a}$, the three parameter interval grey number degenerates to the real number. In fact, the interval grey number and the real number .are special cases of the three-parameter interval grey number.

Its algorithm is similar to interval grey number. Let three-parameter interval grey number $A(\otimes)=[\underline{a},\tilde{a},\bar{a}]$, $B(\otimes)=[\underline{b},\tilde{b},\bar{b}]$, then

$$A(\otimes)+B(\otimes)=[\underline{a}+\underline{b},\tilde{a}+\tilde{b},\bar{a}+\bar{b}]$$

$$A(\otimes)/B(\otimes)\in\left[\min\{\underline{a}/\underline{b},\underline{a}/\bar{b},\bar{a}/\underline{b},\bar{a}/\bar{b}\},\tilde{a}/\tilde{b},\max\{\underline{a}/\underline{b},\underline{a}/\bar{b},\bar{a}/\underline{b},\bar{a}/\bar{b}\}\right]$$

$$\lambda A(\otimes)=[\lambda\underline{a},\lambda\tilde{a},\lambda\bar{a}],\ \lambda>0$$

4.2 Three-parameter interval grey number grey relational model

Suppose that there are n alternative engineering change schemes. They constituted by evaluation schemes set $A=\{a_1,a_2,\Lambda\ ,a_n\}$. The index set $S=\{s_1,s_2,\Lambda\ ,s_m\}$ is composed of m attributes. The index value of scheme a_i under the evaluation index s_j can be expressed as $u_{ij}(\otimes)=[\underline{u}_{ij},\tilde{u}_{ij},\bar{u}_{ij}]$ ($\underline{u}_{ij}\le\tilde{u}_{ij}\le\bar{u}_{ij}, i=1,2,\Lambda\ ,n; j=1,2,\Lambda\ ,m$).The effect evaluation vector of each scheme is $u_i(\otimes)=(u_{i1}(\otimes),u_{i2}(\otimes),\Lambda\ ,u_{im}(\otimes)), i=1,2,\Lambda\ ,n$. The weight of index under each scheme is $w_{i1},w_{i2},\Lambda\ ,w_{im}$, and $\sum_{j=1}^{m}w_{\mathrm{ij}}=1(i=1,2,...,n)$. There are different attribute indexes with different dimensions and measurement standards. In order to increase the comparability of alternatives, it is necessary to normalize the effect evaluation vector of decision alternatives. In this paper, we use the range transformation method to normalize the decision matrix.

For profitable attribute values:

$$\underline{x}_{ij}=\frac{\underline{u}_{ij}-\underline{u}_j^{\nabla}}{\bar{u}_j^{*}-\underline{u}_j^{\nabla}},\quad \tilde{x}_{ij}=\frac{\tilde{u}_{ij}-\underline{u}_j^{\nabla}}{\bar{u}_j^{*}-\underline{u}_j^{\nabla}},\quad \bar{x}_{ij}=\frac{\bar{u}_{ij}-\underline{u}_j^{\nabla}}{\bar{u}_j^{*}-\underline{u}_j^{\nabla}} \tag{1}$$

For cost attribute values:

$$\underline{x}_{ij} = \frac{\bar{u}_j^* - \bar{u}_{ij}}{\bar{u}_j^* - \underline{u}_j^{\nabla}}, \quad \tilde{x}_{ij} = \frac{\bar{u}_j^* - \tilde{u}_{ij}}{\bar{u}_j^* - \underline{u}_j^{\nabla}}, \quad \bar{x}_{ij} = \frac{\bar{u}_j^* - \bar{u}_{ij}}{\bar{u}_j^* - \underline{u}_j^{\nabla}} \tag{2}$$

Where, $\bar{u}_j^* = \max_{1 \le i \le n}\{\bar{u}_{ij}\}, \underline{u}_j^{\nabla} = \min_{1 \le i \le n}\{\underline{u}_{ij}\}, j = 1,2,\Lambda ,m.$

Let the normalized effect evaluation vector be:

$$x_i(\otimes) = (x_{i1}(\otimes), x_{i2}(\otimes), \Lambda , x_{im}(\otimes)), i = 1,2,\Lambda ,n \tag{3}$$

Where, $x_{ij}(\otimes) \in [\underline{x}_{ij}, \tilde{x}_{ij}, \bar{x}_{ij}]$ is a three-parameter interval grey number in $[0,1]$

Recorded that $\underline{x}_j^+ = \max_{1 \le i \le n}\{\underline{x}_{ij}\}$, $\tilde{x}_j^+ = \max_{1 \le i \le n}\{\tilde{x}_{ij}\}$, $\bar{x}_j^+ = \max_{1 \le i \le n}\{\bar{x}_{ij}\}$, $\underline{x}_j^- = \min_{1 \le i \le n}\{\underline{x}_{ij}\}$, $\tilde{x}_j^- = \min_{1 \le i \le n}\{\tilde{x}_{ij}\}$, $\bar{x}_j^- = \min_{1 \le i \le n}\{\bar{x}_{ij}\}(j = 1,2,\Lambda ,m)$. Then the m-dimensional three-parameter non negative interval grey number vectors

$$x^+(\otimes) = \{x_1^+(\otimes), x_2^+(\otimes), \Lambda , x_m^+(\otimes)\}, \quad x^-(\otimes) = \{x_1^-(\otimes), x_2^-(\otimes), \Lambda , x_m^-(\otimes)\} \tag{4}$$

are called ideal optimal scheme effect evaluation vectors and critical scheme effect evaluation vectors respectively. Sun *et al.*(2020)[29]

We assume that the grey interval relational degree of the normalized effect evaluation vector $x_i(\otimes)$ of scheme A_i with respect to the ideal optimal scheme effect evaluation vector $x^+(\otimes)$ is $G(x^+(\otimes), x_i(\otimes))$.And the grey interval relational degree of critical scheme effect evaluation vector $x^-(\otimes)$ is $G(x^-(\otimes), x_i(\otimes))$.Assume that the weights of two grey relational degrees are α_1, α_2 $(\alpha_1 + \alpha_2 = 1)$.Then,

$$G(x_i(\otimes)) = \alpha_1 G(x^+(\otimes), x_i(\otimes)) + \alpha_2 [1 - G(x^-(\otimes), x_i(\otimes))], i = 1,2,\Lambda ,n \tag{5}$$

is the three-parameter grey interval linear relational degree of the effect evaluation vector $x_i(\otimes)$.

$$G(x_i(\otimes)) = [G(x^+(\otimes), x_i(\otimes))]^{\alpha_1} + [1 - G(x^-(\otimes), x_i(\otimes))]^{\alpha_2}, i = 1,2,\Lambda ,n \tag{6}$$

is the three-parameter grey interval product relational degree of the effect evaluation vector $x_i(\otimes)$.

The distribution probability of barycenter point with the highest probability of taking the value of three-parameter interval grey number $x_{ij}(\otimes) \in [\underline{x}_{ij}, \tilde{x}_{ij}, \bar{x}_{ij}]$ is $f(\tilde{x}_{ij}) \ge \sigma$ .Normally, $\sigma \ge 60\%$. If $\sigma \le 60\%$ it indicates that the decision is wrong, and the most likely value needs to be determined again. Based on the center of gravity, we can build a three-parameter interval grey number relational degree evaluation model.(Yan *et al.* (2013)).

Definition 3 for three-parameter interval grey number $x_{ij}(\otimes)\in\left[\underline{x}_{ij},\tilde{x}_{ij},\bar{x}_{ij}\right]$, then

$$\gamma_{ij}^{+}=\frac{3}{5}\times\frac{\tilde{m}^{+}+\eta\tilde{M}^{+}}{\tilde{\Delta}_{ij}^{+}+\eta\tilde{M}^{+}}+\frac{2}{5}\left[(1-\beta)\frac{\underline{m}^{+}+\eta\underline{M}^{+}}{\underline{\Delta}_{ij}^{+}+\eta\underline{M}^{+}}\beta\frac{\overline{m}^{+}+\eta\overline{M}^{+}}{\overline{\Delta}_{ij}^{+}+\eta\overline{M}^{+}}\right] \tag{7}$$

is called the three-parameter grey interval relational coefficient of sub factor. x_{ij} with respect to ideal factor x_j^{+}. $\eta\in(0,1)$ is the resolution coefficient. $\beta\in(0,1)$ is the decision preference coefficient. Where,

$$\underline{\Delta}_{ij}^{+}=\left|\underline{x}_j^{+}-\underline{x}_{ij}\right|,\ \tilde{\Delta}_{ij}^{+}=\left|\tilde{x}_j^{+}-\tilde{x}_{ij}\right|,\ \overline{\Delta}_{ij}^{+}=\left|\bar{x}_j^{+}-\bar{x}_{ij}\right|,\ i=1,2,\Lambda,n;\ j=1,2,\Lambda,m$$

$$\underline{m}^{+}=\min_{1\le i\le n}\min_{1\le j\le m}\underline{\Delta}_{ij}^{+},\ \tilde{m}^{+}=\min_{1\le i\le n}\min_{1\le j\le m}\tilde{\Delta}_{ij}^{+},\ \overline{m}^{+}=\min_{1\le i\le n}\min_{1\le j\le m}\overline{\Delta}_{ij}^{+}$$

$$\underline{M}^{+}=\max_{1\le i\le n}\max_{1\le j\le m}\underline{\Delta}_{ij}^{+},\ \tilde{M}^{+}=\max_{1\le i\le n}\max_{1\le j\le m}\tilde{\Delta}_{ij}^{+},\ \overline{M}^{+}=\max_{1\le i\le n}\max_{1\le j\le m}\overline{\Delta}_{ij}^{+}$$

$$G\left(x^{+}(\otimes),x_i(\otimes)\right)=\sum_{j=1}^{m}w_{ij}\gamma_{ij}^{+},i=1,2,\Lambda,n \tag{8}$$

is called the three-parameter grey interval relational degree of the effect evaluation vector $x_i(\otimes)$ about the ideal optimal scheme effect evaluation vector $x^{+}(\otimes)$.

Definition 4 For three-parameter interval grey number $x_{ij}(\otimes)\in\left[\underline{x}_{ij},\tilde{x}_{ij},\bar{x}_{ij}\right]$,

$$\gamma_{ij}^{-}=\frac{3}{5}\times\frac{\tilde{m}^{-}+\varepsilon\tilde{M}^{-}}{\tilde{\Delta}_{ij}^{-}+\varepsilon\tilde{M}^{-}}+\frac{2}{5}\times\left[(1-\delta)\frac{\underline{m}^{-}+\varepsilon\underline{M}^{-}}{\underline{\Delta}_{ij}^{-}+\varepsilon\underline{M}^{-}}+\delta\frac{\overline{m}^{-}+\varepsilon\overline{M}^{-}}{\overline{\Delta}_{ij}^{-}+\varepsilon\overline{M}^{-}}\right] \tag{9}$$

is called the three-parameter grey interval relational coefficient of sub factor. x_{ij} with respect to ideal facto x_j^{-}. $\eta\in(0,1)$ is the resolution coefficient. $\delta\in(0,1)$ is the decision preference coefficient. Where,

$$\underline{\Delta}_{ij}^{-}=\left|\underline{x}_{ij}-\underline{x}_j^{-}\right|,\ \tilde{\Delta}_{ij}^{-}=\left|\tilde{x}_{ij}-\tilde{x}_j^{-}\right|,\ \overline{\Delta}_{ij}^{-}=\left|\bar{x}_{ij}-\bar{x}_j^{-}\right|,\ i=1,2,\Lambda,n;\ j=1,2,\Lambda,m$$

$$\underline{m}^{-}=\min_{1\le i\le n}\min_{1\le j\le m}\underline{\Delta}_{ij}^{-},\ \tilde{m}^{-}=\min_{1\le i\le n}\min_{1\le j\le m}\tilde{\Delta}_{ij}^{-},\ \overline{m}^{-}=\min_{1\le i\le n}\min_{1\le j\le m}\overline{\Delta}_{ij}^{-}$$

$$\underline{M}^{-}=\max_{1\le i\le n}\max_{1\le j\le m}\underline{\Delta}_{ij}^{-},\ \tilde{M}^{-}=\max_{1\le i\le n}\max_{1\le j\le m}\tilde{\Delta}_{ij}^{-},\ \overline{M}^{-}=\max_{1\le i\le n}\max_{1\le j\le m}\overline{\Delta}_{ij}^{-}$$

$$G\left(x^{-}(\otimes),x_i(\otimes)\right)=\sum_{j=1}^{m}w_{ij}\gamma_{ij}^{-},i=1,2,\Lambda,n \tag{10}$$

is called the three-parameter grey interval relational degree of the effect evaluation vector $x_i(\otimes)$

about the critical scheme effect evaluation vector $x^{-}(\otimes)$.

4.3. Determination of weight

At present, scholars attach great importance to the development and application of subjective and objective empowerment methods in the research of evaluation. The subjective weight reflects the subjective willingness of the evaluation subject, and highlights the degree of distinction between the evaluation objects through index data information. The combination of them will make the result more objective. In this paper, the simplified BWM subjective weighting method and the Gini coefficient weighting method which can better reflect the data difference information are selected for combination weighting.

4.3.1 Determination of weight based on BWM

BWM(best-worst method) is a new method to determine the subjective weight of index proposed by Rezaei in 2014. The most frequently used method in the multiple indexex evaluation is AHP method. In AHP method, any two indexes are usually compared with each other to get the evaluation matrix of indexes, which needs $n(n-1)/2$ times of comparison. The calculation process of it is complicated and will cause certain errors. However, BWM only needs $2n-3$ calculations by selecting the best and the worst indexes and comparing them with other indexes. It simplifies the complicated process of AHP, greatly reduces the amount of data, reduces the mistakes caused by too much data, makes it easier to pass the consistency test, and improves the reliability. The calculation steps are as follows:(Behzad *et al.*(2020))

(1) The best index X_B and the worst index X_W are selected according to experts'opinions in index set $X = \{x_1, x_2, ... x_n\}$.

(2) Experts use 1-9 point scale to score and determine the importance of other indexes relative to the optimal indexes. We construct the comparison vector $C_B =（C_{B1}， C_{B2}, ..., C_{Bj}）$. C_{Bj} represents the importance of the optimal index compared with index j . 1 means C_B and C_{Bj} are equally important. 9 means C_B is extremely important than C_{Bj}.

(3) We need to determine the unimportance of other indexes relative to the worst indexes and construct a comparison vector $C_{\mathrm{w}} =（C_{1w}， C_{B2w}, ..., C_{jw})^T$. Where, C_{jw} represents the least importance of the worst index compared with index j. 1 means C_{jw} and C_w are equally unimportant. 9 means C_{jw} and C_w are extremely unimportant.

(4) From the goal programming model, a mathematical programming formula is established and solved to obtain the optimal index weight $\omega_j^* =（\omega_1^*, \omega_2^*, ..., \omega_n^*）$.

$$\min \max_j \left\{ \left| \frac{\omega_j}{\omega_W} - aB_j \right| \right\}$$
$$s.t. \begin{cases} \sum_{j=1}^{n} \omega_j = 1 \\ \omega_j \geq 0, j = 1,2,...n \end{cases} \quad (11)$$

Where, ω_B is the weight of C_B, C_j is the criterion vector. ω_j is the weight of C_j. ω_B is the weight of C_W. a_{Bj} represents the importance of C_B to C_j; a_{jW} represents the importance of C_j to C_W.

It can be transformed to

$$\min k$$
$$s.t. \begin{cases} \left| \frac{\omega B}{\omega_j} - aBj \right| \leq k \\ \left| \frac{\omega_j}{\omega W} - ajW \right| \leq k \\ \sum_{j=1}^{n} \omega_j = 1 \\ \omega_j \geq 0 \end{cases}, j = 1,2,...,n \quad (12)$$

(5) Calculate the consistency ratio. The obtained K can be represented by K^*, and the consistency ratio Cr (C1 is the given value) can be obtained from $C_R = \frac{k^*}{C_1}$.

The closer of the value is to 0, the better the consistency. When it is 0, it is consistent. If there are p experts participate in the judgment, the final weight will be calculated by weighted average, and the final weight is $\overline{\omega}_j^* = \frac{\sum_{a=1}^{p} \omega_j^a}{p}$.

4.3.2 Weight determination method based on Gini coefficient

(1) Principle of Gini coefficient weighting method

Gini coefficient weighting method is an objective weighting method by calculating Gini coefficient of evaluation index and normalizing Gini coefficient of each index. First of all, the different data of n evaluation objects of a specific evaluation index can be regarded as the income of different levels people. Then the Gini coefficient of a certain index can be calculated. The value of Gini coefficient can reflect the data difference between different evaluation objects. Then, In order to ensure that weight of all indexes are in the range of 0 to 1 and the sum is 1, the Gini coefficient value of each index will be normalized to get the Gini coefficient weight of the evaluation index. Zahng *et al.*(2020).

(2) Gini coefficient weight' calculation of evaluation index .

We assume that G_k is the Gini coefficient of the kth index, Y_{ki} is the ith data of the kth index, and μ K. μK is the expected value of all data of the kth index. Then the Gini coefficient G_k of the kth index is shown as follows:

$$G_k = \sum_{i=1}^{n}\sum_{j=1}^{n}\left|Y_{ki} - Y_{kj}\right|/2n^2\mu_k \tag{13}$$

$$G_k = \sum_{i=1}^{n}\sum_{j=1}^{n}\left|Y_{ki} - Y_{kj}\right|/(n^2 - n) \tag{14}$$

Especially, when the mean value of index data is not 0, the Gini coefficient is calculated by the improved formula (13).When the mean value of the index data is 0, the Gini coefficient of the index is calculated by the original formula (14). Gini coefficient of the index truly reflects the data changes of different evaluation objects of the index.

Gini coefficient weight g_k of the k th index can be obtained by normalizing the Gini coefficient value of each index:

$$g_k = G_k/(\sum_{i=1}^{m} G_i) \tag{15}$$

Where, g_k is Gini coefficient weight of the kth index, G_k is Gini coefficient value of the kth index, and m is the number of indexes.

The advantages of Gini coefficient weighting method are as follows: first, the weight calculation is not affected by the unit dimension of the index, the definition of Gini coefficient itself eliminates the dimensional influence. Second, Gini coefficient value of the evaluation index reflects the difference between any two evaluation objects. Gini coefficient weight reflects the difference between the data of different evaluation objects of an index. And the weight reflects the data information of the index, which meets the requirements of the objective weighting method.

4.3.3 Combination weighting method based on BWM-Gini coefficient

The BWM method determines the index weight according to the subjective preference of the evaluator, and the method of Gini coefficient determines the objective index weight. In order to fully reflect the advantages of the two methods, from the subjective and objective point of view, this paper combines BWM method and Gini coefficient method to determine the comprehensive weight of the evaluation index by linear weighting:

$$W_i^* = \xi W + (1-\xi)W_i = \left[w_1^*, w_2^*, \Lambda, w_n^*\right]^T \tag{16}$$

Where, W_i^* is the comprehensive weight of the decision unit i, ξ is the subjective preference coefficient, $1-\xi$ is the objective preference coefficient($\xi \in [0,1]$), and the specific value of ξ is given by the decision maker according to personal preference.

4.3.4 Steps of complex product engineering change impact evaluation based on three-parameter grey relational degree

To sum up, the three-parameter interval grey relational evaluation algorithm of complex product design change is as follows:

Step1:Constructed the model of complex product change representation based on multi-stage complex network model.

Step2:Determine the evaluation index.

Step3:Standardize the original three-parameter interval grey number effect evaluation index, and obtain the standardized effect evaluation vector formula of each scheme.

Step4:Solve the ideal optimal solution for the decision-making problem and the effect evaluation vector $x^{+}(\otimes)$ and the critical solution $x^{-}(\otimes)$.

Step5:Obtain the three-parameter grey interval relational coefficient vector of each scheme, the ideal scheme and the critical scheme.

Step6:Solve the BWM and Gini coefficient models, and obtain the weight of each scheme under different attributes.

Step7:Calculate the three-parameter interval grey number relational degree $G(x^{+}(\otimes), x_i(\otimes))$ and $G(x^{-}(\otimes), x_i(\otimes))(i = 1,2,\Lambda\ ,n)$ between each scheme and ideal scheme and critical scheme, and calculate the three-parameter grey interval linear relational degree or three-parameter grey interval product relational degree $G(x_i(\otimes))(i = 1,2,\Lambda\ ,n)$ of each scheme.

Step8: The schemes are sorted according to the relevance degree $G(x_i(\otimes))(i = 1,2,\Lambda\ ,n)$. The scheme corresponding to the maximum correlation degree is the optimal one.

The flow of this algorithm is shown in the Figure 5.

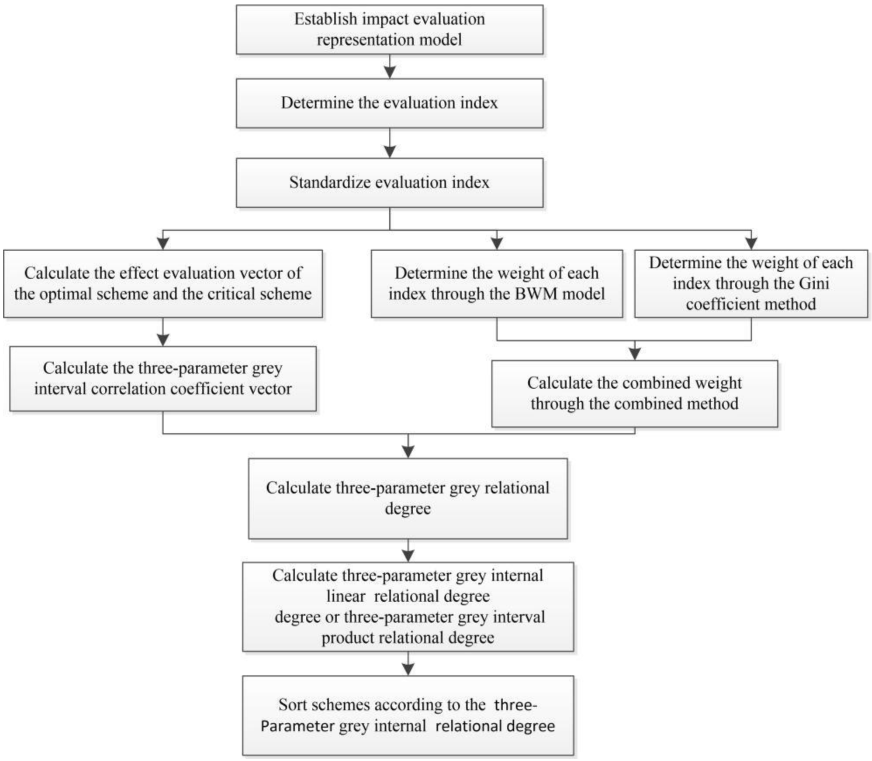
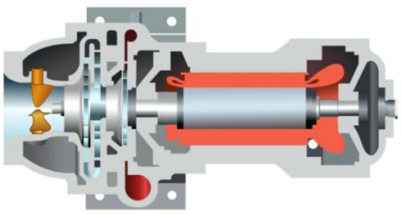


Fig.5 Three-parameter interval grey number grey relational evaluation model algorithm

5. Case study

The high-speed permanent magnet synchronous frequency conversion centrifugal high-power chiller of G enterprise is a typical complex product. (It is shown in the figure 6.a.)The unit has reached the "international leading"level, the annual comprehensive efficiency of the unit has been increased by more than 65%, and the energy saving has been more than 40%. Large units involve many parts and complex products. When engineering change occurs, there are many related impacts occur. This paper analyzes the engineering change of high speed permanent magnet synchronous variable frequency centrifugal compressor of its large unit. The composition and structure of main parts are shown in the Figure 6.b. The main parts of permanent magnet synchronous centrifugal compressor are shown in Table 1.



(a) Physical picture of large permanent magnet synchronous centrifugal unit

(b) Sectional view of permanent magnet synchronous centrifugal compressor

Fig. 6 Large permanent magnet synchronous centrifugal unit and permanent magnet synchronous centrifugal compressor

Table 1 Main parts and node name of permanent magnet synchronous centrifugal compressor

Node	parts	Node	Parts
V_1	mainshaft	V_{13}	Bend casing
V_2	impeller rim1	V_{14}	Curved separator
V_3	Roulette1	V_{15}	refluxer separator
V_4	Blade1	V_{16}	refluxer flow channels
V_5	shrink-ring	V_{17}	volute
V_6	fixed collar	V_{18}	impeller rim2
V_7	balance disc	V_{19}	Roulette2
V_8	reinforcement on the back of impeller	V_{20}	Blade2
V_9	thrust disc	V_{21}	stator winding
V_{10}	axle sleeve	V_{22}	stator core
V_{11}	suction chamber	V_{23}	foundation
V_{12}	diffuser	V_{24}	p-m rotor

It is known that part 4 needs to be improved due to increased customer demand. There are 4 changed routes, and the impact evaluation of the changed routes is carried out. The four routes are as follows:Engineering change node route 1:4-3-2-6-5-7-9;Engineering change node route 2:4-3-2-5-8-1;Engineering change node route 3:4-3-15-16-17-24;Engineering change node route 4:1-2-3-4-14-22

The physical schematic diagram of the change routes are shown in Figure 7.

Fig. 7 Physical schematic diagram of the change routes

The normalized three-parameter interval grey number evaluation matrix is:

$$X(\otimes)=\begin{bmatrix} [0.59,0.63,0.65] & [0.61,0.63,0.65] & [0.80,0.82,0.83] & [0.60,0.65,0.70] \\ [0.67,0.85,1.00] & [0.67,0.70,1.00] & [0.73,0.81,1.00] & [0.00,0.73,0.75] \\ [0.00,0.73,0.74] & [0.72,0.76,0.79] & [0.00,0.62,0.63] & [0.64,0.76,0.79] \\ [0.53,0.55,0.59] & [0.00,0.63,0.69] & [0.57,0.58,0.60] & [0.70,0.74,1.00] \end{bmatrix}$$

According to formula (4), the effect evaluation vectors of ideal optimal scheme and critical scheme are obtained:

$$x^{+}(\otimes)=([0.67,0.85,1.00],[0.72,0.76,1.00],[0.80,0.82,1.00],[0.70,0.76,1.00])$$

$$x^{-}(\otimes)=([0.00,0.55,0.59],[0.00,0.62,0.65],[0.00,0.57,0.60],[0.00,0.65,0.70])$$

The weight matrix obtained by expert BWM method is as follows: $W=(w_1,w_2,w_3,w_4)=(0.37,0.16,0.32,0.14)$

The weight obtained from Gini coefficient is as follows: $W=(w_1,w_2,w_3,w_4)=(0.33,0.11,0.31,0.25)$

Then we can calculate the comprehensive weight. this paper takes the preference coefficient 0.4. $W_i^{*}=0.6W_B+0.4W_J$ can be obtained from formula (17). Then we can get the comprehensive weight: $W=(w_1,w_2,w_3,w_4)=(0.35,0.14,0.31,0.18)$

According to equation (8) and equation (10), the grey interval relational degree of each scheme with ideal optimal scheme and critical scheme is obtained as follows:

$G(x^{+}(\otimes),x_1(\otimes))=0.89$, $G(x^{-}(\otimes),x_1(\otimes))=0.88$, $G(x^{+}(\otimes),x_2(\otimes))=0.72$, $G(x^{-}(\otimes),x_2(\otimes))=0.67$

$G(x^{+}(\otimes),x_3(\otimes))=0.82$, $G(x^{-}(\otimes),x_3(\otimes))=0.54$, $G(x^{+}(\otimes),x_4(\otimes))=0.74$, $G(x^{-}(\otimes),x_4(\otimes))=0.80$

The three-parameter grey interval linear relational degree of each scheme is calculated by equation (5): $G(x_1(\otimes))=0.53$, $G(x_2(\otimes))=0.67$, $G(x_3(\otimes))=0.48$, $G(x_4(\otimes))=0.43$.

According to the linear relational degree of three-parameter interval grey number, we can

find that the most relevant to the ideal optimal scheme is scheme 2. Change node route2 is 4-3-2-5-8-1:blade1-roulette1-impeller rim1-shrink-ring-reinforcement on the back of impeller-mainshaft. The physical schematic diagram of the change route 2 is shown in Figure 8. We can find that the choice of engineering change route is in line with the reality.

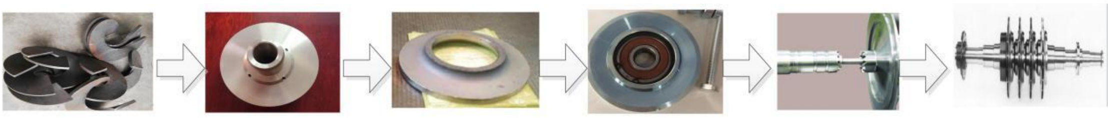


Fig. 8 Physical schematic diagram of change route 2

6. Conclusion

Based on the multi-stage complex network, this paper describes the change impact of complex products, and constructs the evaluation index system. The three-parameter interval grey relational model is improved and applied to change impact evaluation. The research of this paper realizes the objective evaluation of the impact of change. It makes up for the problem that the traditional impact evaluation research mainly depends on the experience of designers. The three -parameter grey relational model is used to evaluate the change impact of complex products, which improves the accuracy of the evaluation of impact on complex product engineering change, and makes up for the shortcomings that the results are not accurate enough to fit the actual situation in the current study of change impact evaluation based on real number model. In addition, the three-parameter interval grey number is more in line with the actual situation in the process of complex product change. Compared with interval grey number, it highlights the "center of gravity" point with the greatest possibility of grey number value, and makes up for the lack of "information" of grey number. Based on the analysis of the classic three-parameter interval grey relational evaluation model, this paper studies the problem of the weight value. Considering from both subjective and objective aspects, the scientific combination of BWM weighting method and Gini coefficient weighting method is feasible and more fair and objective.

On the basis of evaluation system of the complex product change propagation impact, further research work can be carried out in the future. For example, we can combine multi-stage network with product engineering, behavior, structure and other elements to form a complete change evaluation system. Then we can preferably improve the efficiency of product engineering change decision-making and apply the three-parameter interval grey relational evaluation model to complex product.

Declarations

(1)Ethical Approval:This article does not involve the content of violating ethics and morality.

(2)Consent to Participate and Consent to Publish:All authors have read and agreed to participate and publish the manuscript.

(3)Authors Contributions:Conceptualization:Weiming Yang,congdong Li and Yinyun Yu;Model:Weiming Yang,congdong Li and Bingjun Li;Algorithm design:Weiming Yang;Writing, review and editing: Weiming Yang,congdong Li ,Yinyun Yu and Bingjun Li.

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(5)Competing Interests:The authors declare that they have no conflict of interest.

(6)Availability of data and materials：All data generated and materials or analyzed during this study are included in this published article.

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Figures

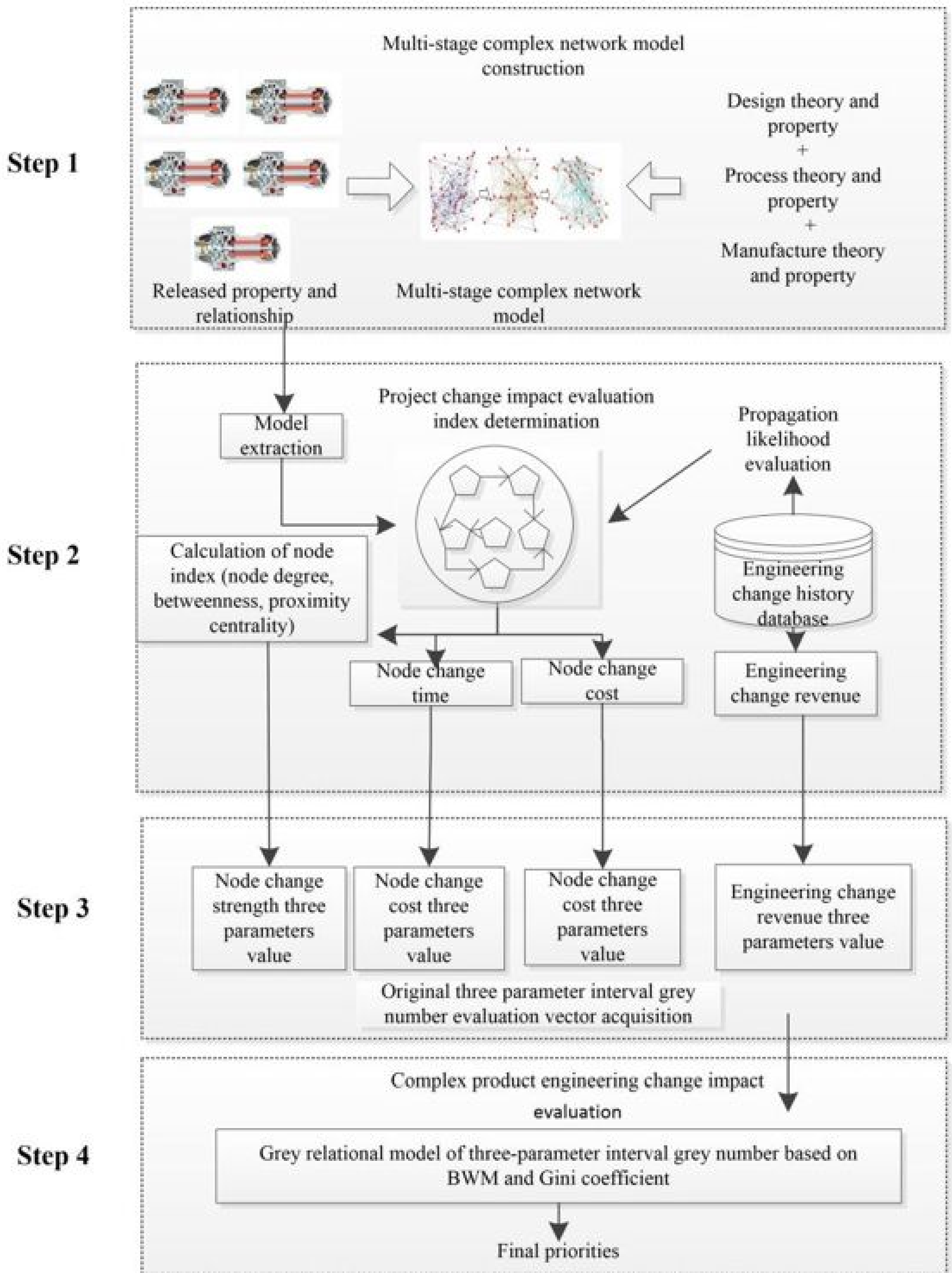

Figure 1

Framework of the proposed complex product engineering change impact evaluation method.

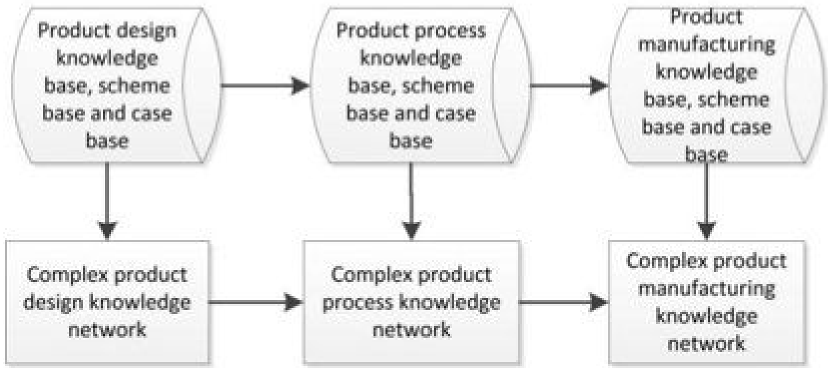

Figure 2

Multi-stage complex network of complex product

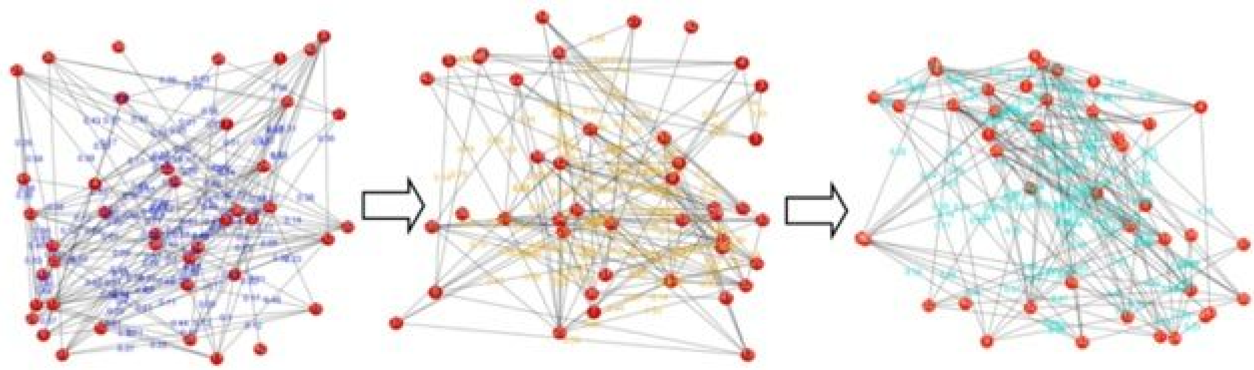

Figure 3

Multi-stage complex knowledge network

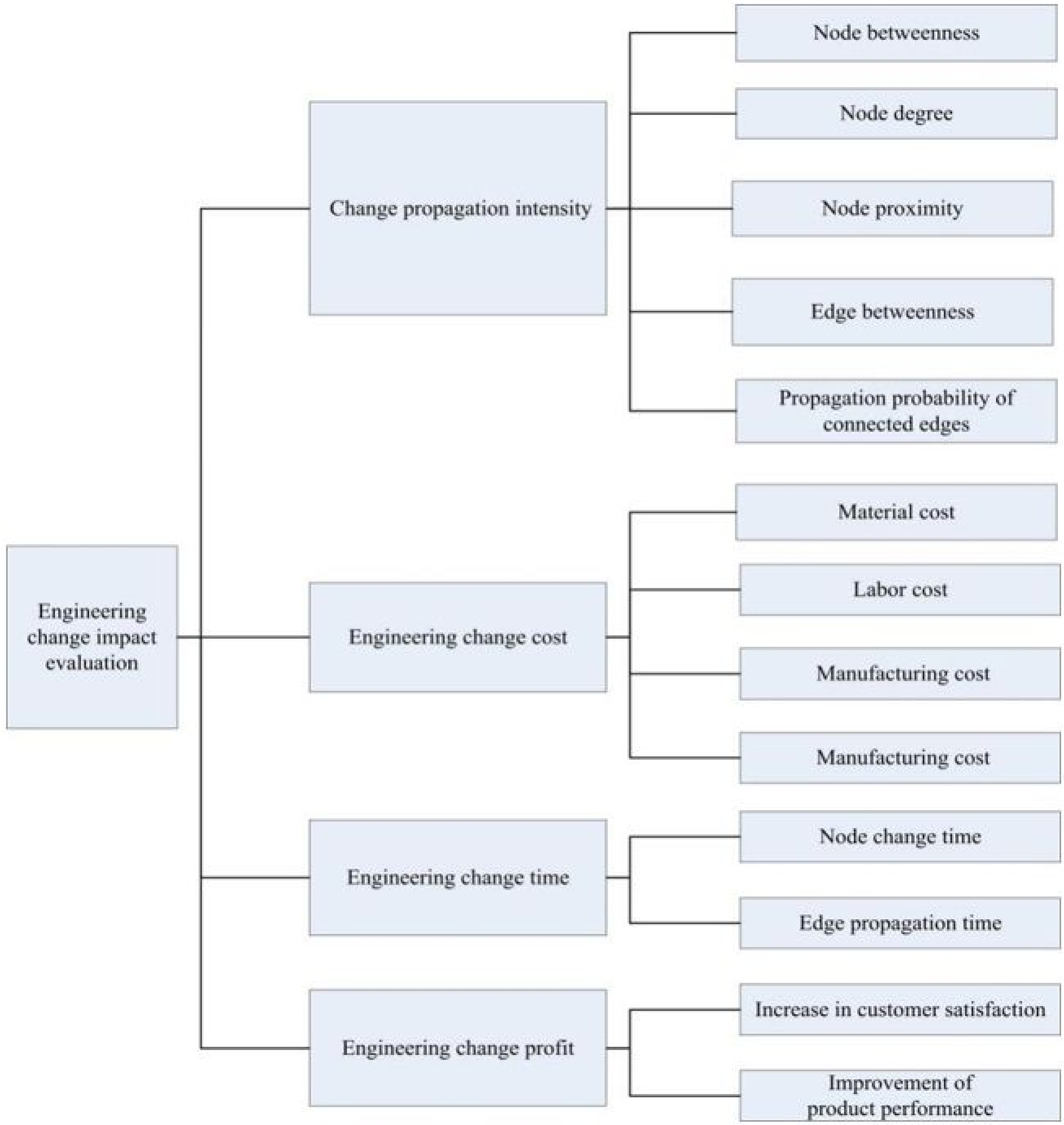

Figure 4

Evaluation indexes of engineering change impact

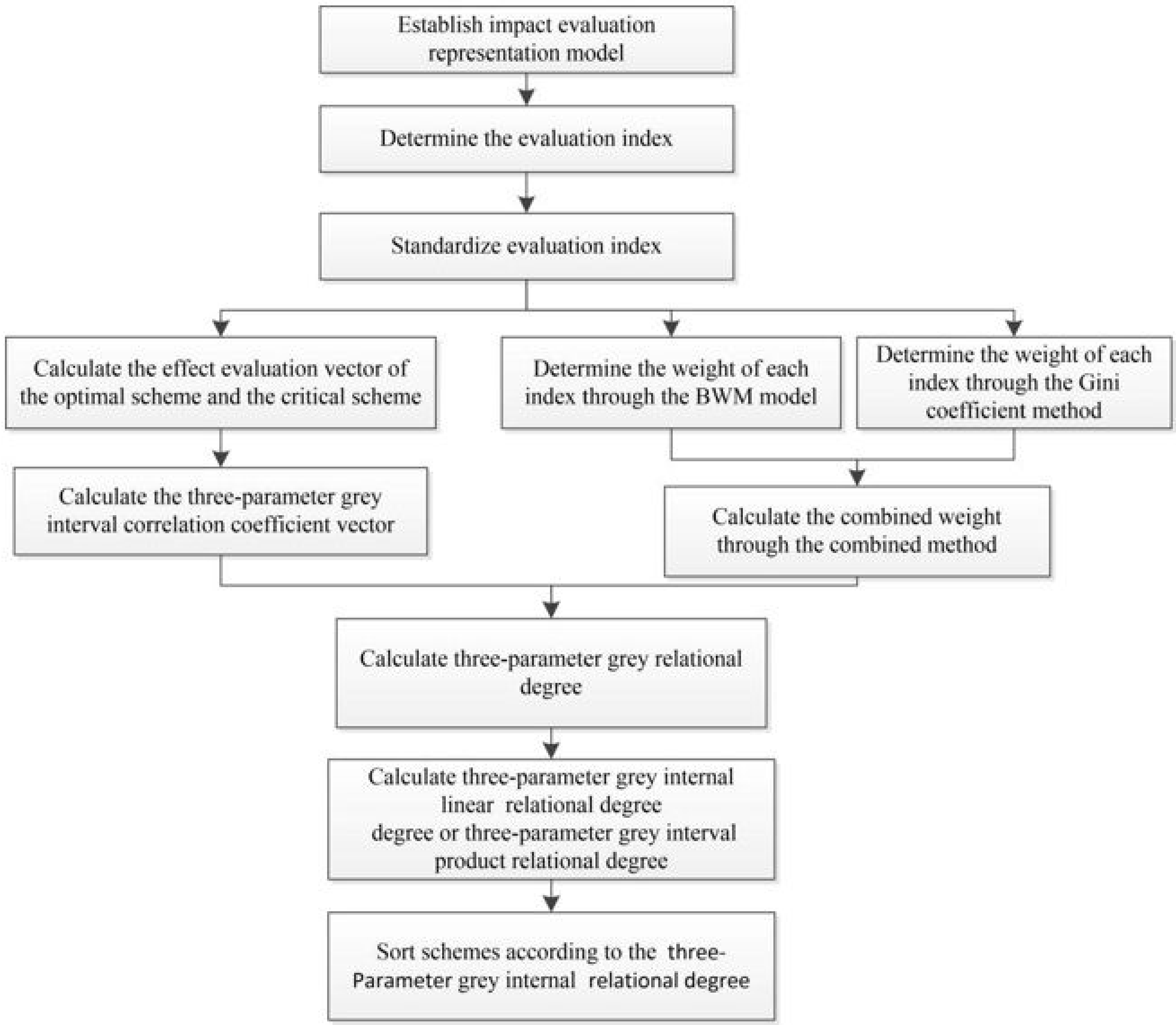

Figure 5

Three-parameter interval grey number grey relational evaluation model algorithm

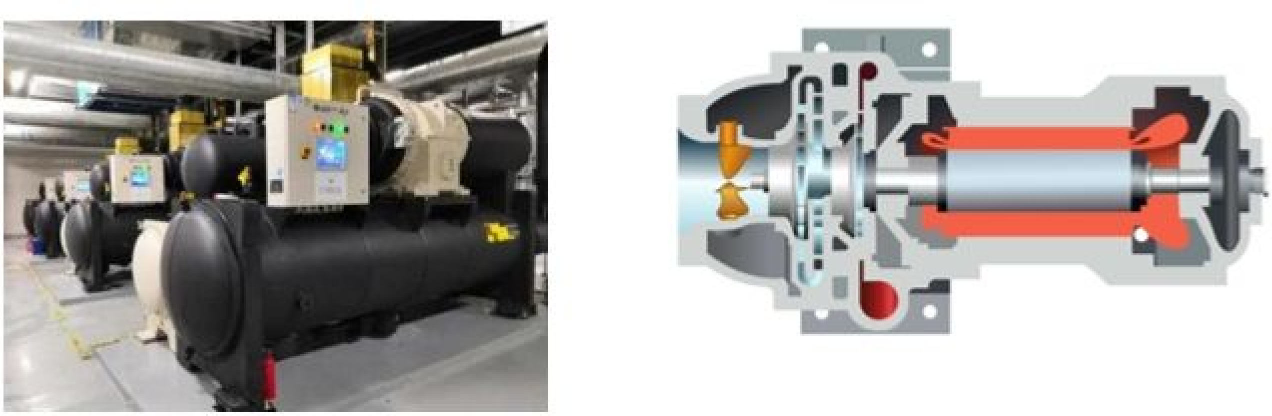

Figure 6

(a) Physical picture of large permanent magnet synchronous centrifugal unit (b) Sectional view of permanent magnet synchronous centrifugal compressor

Figure 7

Physical schematic diagram of the change routes

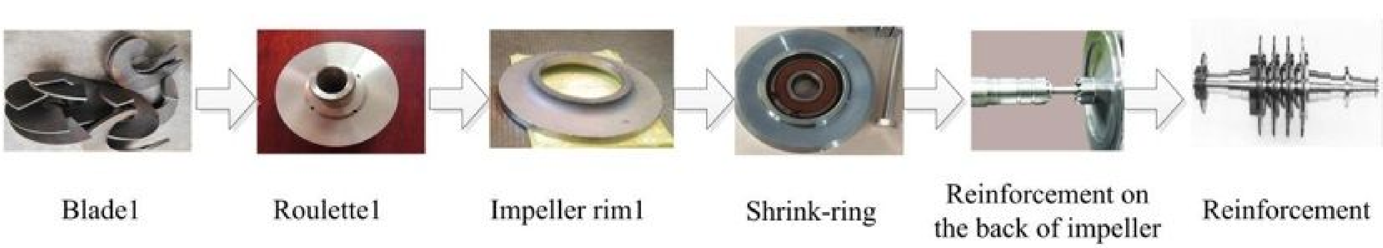

Figure 8

Physical schematic diagram of change route 2