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Improving product redesign efficiency in the detailed design phase: a structure variation map based on customer environment requirements

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Abstract

Aim: The aim of this study is to shorten the product design and development cycle to meet the continuous change and growth of customer environmental requirements.

Methods: The applied research method introduces the concept of the inheritable structure of green products through structural similarity theory and quantitates environmental performance. Additionally, based on the analysis of the obtained customer ecological requirements, a hierarchical mapping method for customer requirements-environmental performance weight-product structure is proposed, which achieves the rapid mapping of customer requirements (CRs) to product structure in the product design process. Then, four mutation operation methods (combination, decomposition, replacement, and material change) are combined with a genetic algorithm, and a method for generating a product structure mutation map is proposed to solve the problem of the non-inheritance of some structures in the product design process. Finally, considering the transmission shell as an example, the validity and feasibility of the method are verified.

Results: The case study showed that the overall mass of the rear derailleur dropped by 27.58 kg, and the environmental performance of the transmission was mainly related to its mass; hence, the proposed improvement method effectively improved the environmental performance of the transmission.

Conclusion: The hierarchical mapping method for customer requirements-environmental performance weight-product structure and the generation method for the product structure variation diagram proposed in this study can shorten the product design and development cycle. This research can provide theoretical and methodological support for product design and development.

Keywords: Customer environment requirements, inheritable structure, environmental performance, hierarchical mapping, structural variation

INTRODUCTION

With increasing customer environmental requirements (CERs), the speed of renewal of mechanical products is also accelerating; hence, designers are also updating the design of mechanical products. To meet different design requirements, designers need to improve the performance of new products (including environmental protection performance) based on the original products. This work is significant for product improvement and alternative design under the condition of ecological awareness.

The key to an enterprise winning the market is whether it can respond quickly to rapidly growing customer requirements (CRs) and reflect them in the product. Therefore, companies should determine the product structure that needs to be improved, reduce the product redesign time, and shorten the product design cycle. In recent years, requirements for the environmental performance of products have gradually attracted the attention of customers and designers. Therefore, combining the sustainable design idea with a CER analysis and processing method is very important for conducting CR analysis for sustainable design. At present, in terms of product demand analysis, current research is quite sufficient. Manesh *et al.* proposed a requirement analysis method for holonic manufacturing systems based on the virtual reality method, aiming to help designers of such systems throughout the system design and development process[1]. Nahm *et al.* proposed a new method to prioritize CRs in the quality function deployment (QFD) process, which developed two new sets of rating methods called the customer preference rating and customer satisfaction rating[2]. Wang and Tseng used Bayesian factor analysis to quantify the change in the cost estimation relationship and finally predicted the cost estimation relationship[3]. Shi *et al.* proposed a product design-oriented CRs classification method, which uses the big data of online customer reviews of products to classify CRs accurately and efficiently[4]. Zheng *et al.* proposed a weighted interval rough number method, which can objectively and accurately explain various CRs preferences[5]. Huang *et al.* proposed an online review product feature extraction model based on multi-feature fusion called the product feature extraction based on multi-feature fusion model[6]. Zhou *et al.* proposed a user experience-oriented smart service requirements analysis framework, which can be used to develop smart product service systems (PSS)[7]. Zhu *et al.* developed a requirement-driven PSS using requirements analysis and knowledge management techniques[8].

Although current research on CRs is relatively complete, most of the research focuses on requirements such as product performance, function, and appearance, whereas there is relatively little research on environmental requirements. Bereketli *et al.* proposed a multi-aspect QFD for environment (QFDE) to determine improvement strategies by considering not only the end users' requirements but also the environmental stakeholders' requirements[9]. Zhang *et al.* used the sensitivity analysis method to obtain the weights of various ecological design engineering parameters corresponding to CERs[10]. Younesi *et al.* proposed an integrated QFDE, fuzzy decision-making trial and evaluation laboratory, and fuzzy analytic network process for sustainable product design to help companies to identify the best design criteria for a specific product[11]. On the premise of a deteriorating environment, it is essential to analyze CERs. Considering the multi-faceted and uncertain characteristics of CERs, it is more challenging to conduct demand analysis directly[12]; hence, it is necessary to transform them into engineering features that can be used now. Yuan *et al.* proposed the concept of requirement units and their granularity to decompose the customer relationship model[13]. Gao *et al.* proposed a parameter transformation method of customer green requirement engineering based on data envelopment analysis and grey relational analysis[14]. Sheng *et al.* established the relationship between product modules and CRs, and transformed CRs into parameters that can be directly used in modular design[15]. Ma *et al.* proposed a new integrative, multidisciplinary CR modeling approach to capture and describe the common understanding of CRs[16]. Li *et al.* proposed a formal modeling method for cloud manufacturing service composition based on process calculus[17]. Razavi *et al.* provided a new model-independent feature engineering framework for theft detection in smart grids[18]. Zhang *et al.* proposed a new comprehensive numerical solution method by combining the finite element model with several optimization algorithms[19]. Sun *et al.* built a stochastic frontier model of energy demand based on the determinants of national patent stocks, international knowledge spillovers, and the interaction between them[20].

After obtaining the product engineering features or function, they need to be transformed into the description of the specific structure of the product. The mapping of product function to structure needs to be achieved. Cao *et al.* established the extended-effect driven function-behavior-structure and function design process based on this model to support functional recognition, function decomposition, and function-to-structure mapping[21]. They developed a computer-aided function design software system. Feng *et al.* defined parallel meta-automata and feedback meta-automata models[22]. With the help of disjunctive and reversal operations of weighted automata, the series solution, parallel solution, and feedback solution of functional semantic units were obtained. Based on research on PSS, Chang *et al.* proposed the mapping network model integration service and further discussed the integration mapping process from the perspective of network modeling[23]. Most current research methods have certain subjectivity for the above transformation and mapping, which is not conducive to the rapid and accurate response to new CRs. All the above processes are used to meet the needs of new customers, which is the ultimate goal of this study. It is important to make some structural changes and improvements to satisfy the new CRs after processing CRs and mapping them to the product structure.

As a tool to improve the structure, product variant design has many research results. Bai *et al.* analyzed the correlation between the variation structure and inherent structure in product innovation design[24]. They proposed a structural variation design method based on inherent structure retrieval at the level of the design model. AlGeddawy *et al.* proposed a product platform design model, which can analyze each structure's physical commonness, determine the product's inherent structure, and obtain the typical characteristics of the variation structure[25]. Qiao *et al.* established a product structure knowledge base suitable for variant design, and determined the dynamic link between variant and inherent structures[26]. Gong *et al.* used the product module function extension transformation method and function-behavior-structure iteration mapping[27]. They adopted the correlation transformation method, effectively achieving the inherent module structure's variation design. Tai *et al.* proposed two evolutionary optimization methods for the structural design of flexible mechanisms[28]. Generally, the current process of product design considering CRs is more complicated. The reason is that the design process also reconsiders factors that have no influence on the design result, which not only increases the overall design workload but also delays the design process. Existing mapping methods that convert CRs into environmental performance weights remain subjective and the mapping results are vulnerable to human factors. With current environmental problems becoming increasingly serious and people pursuing the environmental performance of products, it is of great importance to conduct research on the improvement of environmental performance in product improvement design, which can reduce the workload of redesign when new environmental requirements arise and improve R&D efficiency.

METHODS

To solve the above problems, in this study, similarity theory, which was proposed by Zhou, and environmental performance quantitative analysis are used to propose the concept of structure inheritability[29]. When improving a product, inheritable structures cannot participate in the structural improvement process, and the remainder of the structures that do not meet the requirements are only enhanced, which shortens the cycle of product redesign. Because product improvement is inseparable from CRs, in this study, a hierarchical mapping method for CRs-environmental performance weight-product structure is proposed to reduce the subjectivity and complexity in the product design process. The probability of mapping CRs to systems that need to be improved is obtained using hierarchical mapping. Four structural variation methods are proposed for the product structures that need to be improved, product structure variation maps are generated combined with a genetic algorithm (GA), and the structures are finally improved. The overall research scheme of the study is shown in Figure 1.

INHERITABILITY OF GREEN PRODUCTS

Identification of the inheritability of the product structure

Definition 1: Structural element.

A structural element is the smallest unit that makes up a mechanical part or structure.

Definition 2: Structural element feature.

The structural element feature is the type of a specific structural element.

Definition 3: Common feature.

The common feature of structures refers to the common structural element features of two or more mechanical products.

Definition 4: Parent structure.

As shown in Figure 2, structural elements A_1, B_1, …, and N_1 are called the parent structures of common feature 1, denoted by P_{C1}.

Definition 5: Inheritable structure.

The common structural features of environmental performance that meet the criteria are called inheritable structures. As shown in Figure 2, after quantitative environmental performance analysis, common feature 1, which meets the standard, is called the inheritable structure of structural elements A_1, B_1, …, N_1. The extraction of common features of products and the quantification of environmental performance are described in the following two sections.

The following criteria should be met when identifying the inheritance of the product structure:

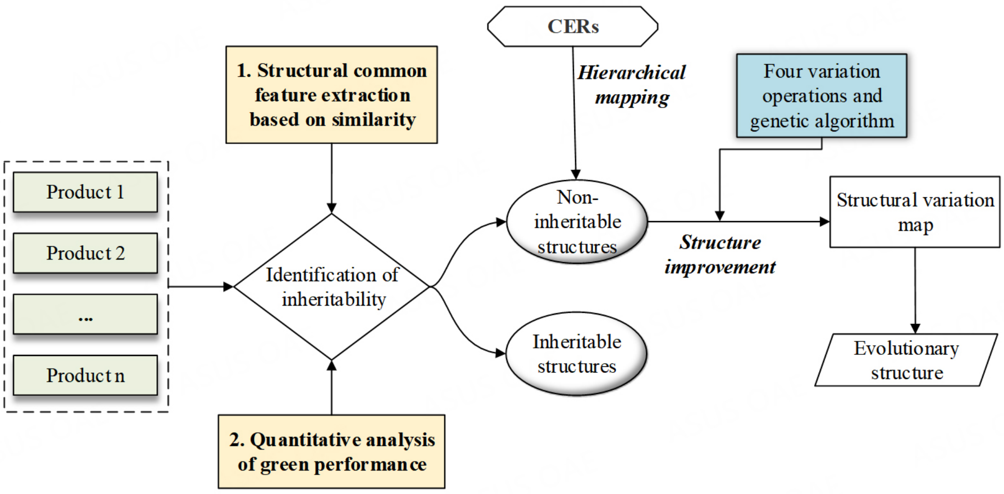


Figure 1. Overall research scheme.

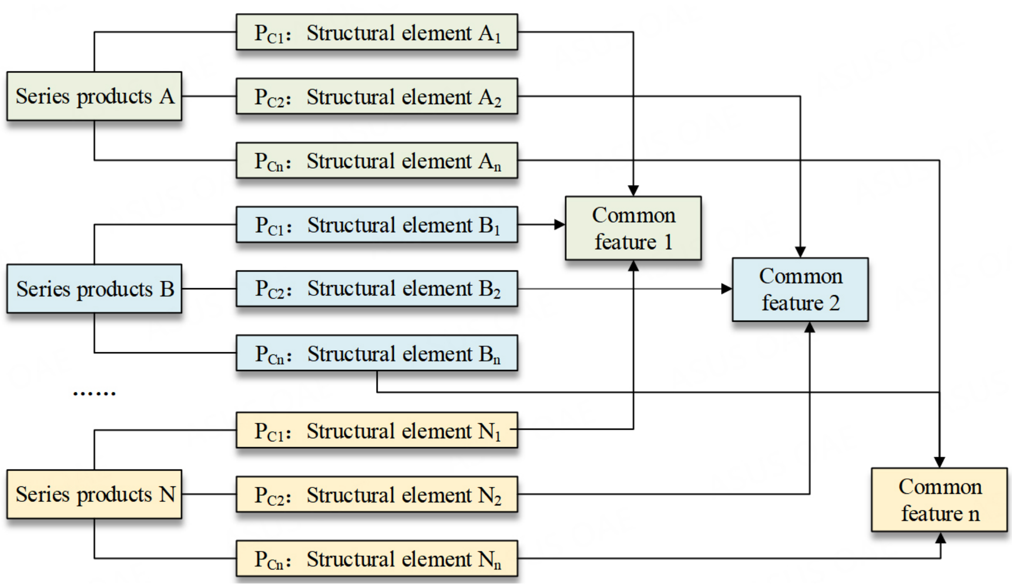


Figure 2. Schematic diagram of product structure feature extraction.

(1) Functional criteria

To ensure the accuracy and rationality of evolutionary products, the inheritable structures should provide the function of the original parent structures.

(2) Structural criteria

The inherited and other structures in the parent structures should satisfy the interference minimization principle, and the connection relationship is universal.

(3) Sustainable criteria

Inherited products must conform to sustainable standards, including material selection, disassembly, recyclability, energy-saving, and environmental protection laws.

Extraction of common features of the product structure

Structural common feature extraction principle

Different structures have different common features, but generally, the extraction of common structural features meets the following criteria:

(1) Similarity criterion

The premise of extracting common features among different structures is that these structures satisfy the principle of similarity. In Section "3.2.2", the assessment method for structural similarity is introduced in detail.

(2) Structural element criteria

The extracted common features must also be features of structural elements, and they can simultaneously reflect the original structural features.

The schematic diagram for structural common feature extraction is shown in Figure 2.

Structural similarity

Structural similarity is the premise of extracting the common features of structures. The steps for structural similarity analysis are as follows:

(1) Construct similar elements

Suppose that system A consists of elements a_1, a_2, ..., a_K and system B consists of elements b_1, b_2, ..., b_L. Then, according to the relationship between the system and the set, the sets of elements in systems A and B are denoted by A and B, respectively:

$$A = \{a_1, a_2, \cdots, a_K\} \tag{1}$$

$$B = \{b_1, b_2, \cdots, b_L\} . \tag{2}$$

If an element a_i in system A and an element b_j in system B form a similar element, it is recorded as *a* set u:

$$u = \{a_i, b_j\} . \tag{3}$$

Similarly, N similar element sets constitute a set U:

$$U = \{u_1, u_2, \cdots, u_N\}. \tag{4}$$

According to intersection theory, we obtain

$$U = A \cap B. \tag{5}$$

(2) Quantitative analysis of similar features

The similarity degree of similar elements is a function of the number of similar features and the similarity ratio of eigenvalues among elements. Assuming that the k features of element a_i constitute set a and the l features of element b_i constitute set b, according to set theory, the set of similar features between elements a_i and b_i is the intersection u of set a and set b:

$$u = a \cap b. \tag{6}$$

The union s represents the set of all features of elements a_i and b_i:

$$s = a \cup b. \tag{7}$$

The number of elements in set a is defined as $\#(a)$, the number of elements inset b is defined as $\#(b)$, the number of elements in set u is defined as $\#(a \cap b)$, and the number of elements in set s is defined as

$$\#(s) = \#(a \cup b). \tag{8}$$

Therefore, there are similar feature numbers, as follows:

$$\#(u) = \#(a \cap b) = n. \tag{9}$$

The cardinality of set s is $\#(s) = \#(a \cup b) = \#(a) + \#(b) - \#(u)$, and the similarity of similar feature numbers is recorded as $q(u_i)_n$; it can be expressed as

$$q(u_i)_n = \frac{\#(a \cap b)}{\#(a \cup b)} = \frac{\#(u)}{\#(a) + \#(b) - \#(u)}. \tag{10}$$

Assume that the numbers of features of similar elements a_i and b_i are k and l, respectively. Let the number of features of similar element a_i be equal to k and the number of features of b_i be equal to l. The number of all features satisfies $\#(a \cup b) = k + l - n$ and the similarity of the number of features is expressed as

$$q(u_i)_n = \frac{n}{k+l-n}. \tag{11}$$

(3) Calculation of the feature similarity degree

Assuming that similar elements have n similar features, combined with similar feature metrics, the proportional coefficients of n eigenvalues for the i_{th} similar element can be recorded as

$$r_{i1}, r_{i2}, \cdots, r_{in}.$$

Considering the different effects of each feature on similar elements, taking the weights of features as d_1, d_2, ..., d_n, the weights are determined by referring to the method of determining the weights of fuzzy similarity elements. Then, the similarity degree of multiple features of similar elements is recorded as $q(u_i)_s$, and the results are as follows:

$$q(u_i)_s = \sum_{j=1}^{n}(d_1 r_{i1} + d_2 r_{i2} + \cdots + d_n r_{in}) = \sum_{j=1}^{n} d_j r_r. \tag{12}$$

When the similar element value and eigenvalues can be processed accurately, the exact similarity element value $q(u_i)$ can be calculated by referring to the typical merging algorithm as follows:

$$q(u_i) = \frac{\#(u)}{\#(a) + \#(b) - \#(u)} \sum_{j=1}^{n} d_j r_{ij} = \frac{n}{k+l-n} \sum_{j=1}^{n} d_j r_{ij}, \tag{13}$$

Where $0 \le q(u_i) \le 1$, $0 \le d_j \le 1$, $\sum d_j = 1$,

$$q(u_i) = \begin{cases} q(u_i) = 1, & k = l = n,\ r_{ij} = 1; \\ 0 < q(u_i) < 1, & 0 < n \le min(k, l),\ 0 < r_{ij} < 1; \\ q(u_i) = 0. & n = 0,\ r_{ij} = 0. \end{cases} \tag{14}$$

The values of similar elements can be determined as follows:

When $q(u_i) = 1$, this indicates that similar elements are equal.

When $0 < q(u_i) < 1$, $q(u_i)$ represents the similarity degree of elements.

When $q(u_i) = 0$, the elements are different.

Quantitative analysis of the product structure and environmental performance

To optimize the environmental performance of the product, it is necessary to conduct a quantitative analysis of environmental performance. Simultaneously, the quantitative analysis of environmental performance for the product structure is a prerequisite for the inheritability of product structures. In this study, typical environmental performance indicators, such as dismantling, recycling, and toxic substance content of the transmission shells, are analyzed.

As a set of gearshift devices used to coordinate the engine speed and the actual speed of the wheel, the transmission is used to fully achieve the engine's best performance. The transmission can produce different transmission ratios between the engine and the wheel during the driving process of the vehicle. The machine can work in its best dynamic performance state as a result of shifting gears. Additionally, the transmission shell is an essential component for carrying complex internal parts and plays a vital role in the design of a product. When considering the sustainable design of the transmission shell, the first step is to consider its disassembly performance. Compared to poor disassembly performance, good disassembly performance means simple disassembly process, less energy consumption and less pollution, recycling performance should be regarded during disassembly because the parts obtained from disassembly are mainly used for recycling. Finally, researchers should consider the content of toxic substances. If the toxic substance content is too high, it will cause great harm to the environment or the human body after abandonment. This is the reason that these three indicators were chosen as environmental indicators in this study.

Disassembly performance

Compared to poor disassembly performance, good disassembly performance means the product has less environmental impact during disassembly. In this study, disassembly performance is quantified from the following indicators: disassembly time, disassembly tools, disassembly fixture, structural accessibility, disassembly technical difficulty, toxicity prevention in disassembly, and disassembly force. The specific quantitative indicators are shown in Table 1.

The disassembly performance quantification formula is

$$GP_1 = \sum_{j=1}^{m}\sum_{i=1}^{n} w_j S_i / 7 , \tag{15}$$

where GP_1 is the quantitative index of structural unit disassembly performance; w_j is the weight value of the *j-th* index of the structural unit, which is given by the expert; and S_i is the evaluation scale of the *i-th* index of the structural unit.

Recycling performance

From the life-cycle perspective, the product structure's recycling performance is mainly reflected in the

Table 1. Disassembly performance indicator quantization

Index	Evaluation scale					
	25	20	15	10	5	0
Disassembly time	< 5 s	25 s	50 s	90 s	140 s	> 210 s
Disassembly tool	Unnecessary	Simple	Complex	Manufacturers provide	Special	Temporary
Disassembly fixture	Unnecessary	Single-handedly	Both hands	Pliers	Capstan	Complex machine
Structural accessibility	Along the Z axis	X/Y axis	Depth is greater than 38 cm	From the bottom	Two-way	Invisible
Disassembly technology difficulty	Unnecessary	< 20 s	< 30 s	Technical discussion	Contact with the original manufacturer	Professional training
Toxicity prevention in disassembly	\	Glove	Mask	Special overalls	Air supply	Isolation
Disassembly force	Unnecessary	A small amount of force	Positive force	Leverage	Low-impact force	High-impact force

environmental impact on parts, materials, and non-renewable resources. Good recycling performance means the maximum recycling of features and materials, and non-renewable resources have a minimal ecological impact. The recycling method for the product structure and the primary considerations are shown in Table 2.

The structural unit recycling performance quantification formula is

$$GP_2 = \sum_{j=1}^{m} \sum_{i=1}^{n} w_j S_i / m \ , \tag{16}$$

where GP_2 is the structural unit recycling performance; w_j is the weight value of the structural unit recycling factor j; S_i is the evaluation value of the recycling factor; and m is the number of recycling factors involved in the recycling of the structural unit.

Toxic substance content

Toxic substances are evaluated and quantified according to the content range of the substances. Table 3 is the quantitative table of toxic substances.

GENERATION METHOD FOR THE PRODUCT STRUCTURE VARIATION MAP

The inheritable and non-inheritable structures of products can be obtained by judging the inheritability of products, including the extraction of common features of the product structure and quantitative analysis of environmental performance. Because of the non-inheritable structure, a method is proposed in this study to generate a product structure variation map. From the perspective of CERs, through mapping the requirements to the structure, the structure that impacts the environment is redesigned (variation). Finally, a variation map is generated that enables product improvement.

Mapping CERs to the product structure

The inheritable structure is obtained by analyzing the inheritability of the green product structure. For the remaining non-inherited structure, the product structure needs to be improved to meet the CERs. Before

Table 2. Recycling methods for the product structure and the main considerations

Resource classification	Recycling method	Recycling index	Key elements	Description
Renewable resource	Parts recycling and reuse	8	Service life of parts	The service life of the components in the structural unit is as close as possible to facilitate the overall recycling and reuse of the structural unit
	Material recycling	6	Material compatibility	Components with good compatibility can be classified into one group in order to facilitate the overall recycling of component materials
			Recycling economy	Components with detailed recycling value are grouped into one group to recycle materials with high value as far as possible, so as to improve the efficiency of product recycling
Non-renewable resources	Incineration	3	Waste	Many environmentally harmful wastes are produced during incineration
			Energy	The energy produced by incineration can be utilized, and the non-renewable resources with high value of incineration should be incinerated
	Waste and landfill	1	Environmental impact of waste	After waste or landfill, the impact of materials on the environment is generally negative. Components with little impact on the environment should be selected as far as possible for wasting or landfilling

Table 3. Quantitative table of toxic substances

Evaluation index	Evaluation score				
	1	3	5	7	9
Content of toxic substances (ppm)	> 1000	1000~500	500~200	200~100	< 100

the structural improvement, the relationship between the CERs and the structure that needs improvement should be determined. In this study, a hierarchical mapping method for "CRs- environmental performance weights-product structure" is proposed. The steps are as follows:

Transformation of CERs to environmental performance weights:

First, the fuzzy analytic hierarchy process (FAHP) is used to determine the importance of CRs $a = \{a_1, a_2, ..., a_m\}$. Second, QFDE is used to transform CRs into environmental performance, and the relationship between CERs and environmental performance weights is obtained.

The relationship between CERs and environmental performance weights is established based on data mining: a multi-layer perceptron neural network model is used to simulate the mapping process from CR data to environmental performance weights. After the model is established successfully, the ecological performance weights can be obtained quickly when new requirements are input.

Mapping environmental performance weights to structures: The mapping of environmental performance weights to structures can be expressed as

$$S = f(EP) \tag{17}$$

$$S = (EP, S, C), \tag{18}$$

where S represents the product structure set, and the output from environmental performance to the product structure may have multiple results or may be an empty set; f represents the solution process; environmental performance EP and structure S are used as inputs to the solution process, which results in a product that meets environmental performance requirements in addition to structural requirements; and C represents the basis for judging the validity of the mapping process.

Product structure features are key to the mapping relationship between environmental performance and structure. In this study, mapping rules are established for environmental performance requirements and product structure features based on the idea of similar matching between environmental performance and structure. The mapping steps are as follows:

First, the scope of environmental performance is determined, that is, whether disassembly performance is the disassembly performance of the product or a part, and whether recycling performance refers to the recycling performance of the material or the part. The range of environmental performance is represented by set $EP = \{EP_1, EP_2, ..., EP_n\}$, where EP_i is environmental performance.

After identifying the environmental performance features, the corresponding part feature matrix $Ms = (S_1, S_2, ..., S_n)$ must be constructed if the mapping is to be achieved.

The probability matrix from environmental performance to the structure is constructed. In this study, the improved method proposed by Ma is used[30]:

$$P_{ij} = \frac{1}{n}\sum_{i=1}^{n} f(x,[a_i,b_j]) \bullet \frac{b_i - a_j}{B_i - A_j}, \tag{19}$$

where $[a_i, b_j]$ is the numerical range mapped to a structure for a certain type of environmental performance, which is determined by expert scoring; $[A_i, B_j]$ is the largest numerical range available for a certain type of environmental performance, which is defined as $[0, 1]$; n is the number of expert matrices; and $f(x, [a_i, b_j])$ is the mapping from environmental performance to the structure, and then

$$f(x,[a_i,b_j]) = \begin{cases} C, & [a_i,b_j] \\ 0. & [A_i,a_j] \cup [b_i,B_j] \end{cases}. \tag{20}$$

The weight matrix W_{EP} for environmental performance and the environmental performance structure probability matrix $M_p(p_{ij})$ can be used to achieve the qualitative mapping of environmental performance to the structure. The mapping result is that each structure has a certain amount of environmental impact. If the mapping matrix is set as M_f, the formula is

$$M_f = M_p \bullet W_{EP}. \tag{21}$$

Generation process for the structural variation map

Variation operation expression method

Designers can improve product environmental performance by changing the local structure or material properties of existing components. In this study, four structural variation expressions are proposed: combination variation, decomposition variation, replacement variation, and material-changing variation.

The essence of combined variation is to add new structural features to the original structural features, and the generated new features inherit all the information of the original features. The variation method is mainly used for the addition and subtraction of parts, and to improve the ability of disassembly and recycling.

Decomposition variation is the inverse process of combination variation, and divides an original part into several parts according to a particular method. Unlike combination variation, the structural features formed by decomposition not only inherit the original parts' structural features but also produce new features. Decomposition variation is mainly used to improve the parts' machinability, disassembly, and recycling performance.

The replacement variation of structural units refers to replacing structural units that exist in parts with new structural units. The new structure completely inherits the Boolean operation in the original part and its dependence on the adjacent structure. Material-changing variation is a product structure variation method that changes the material of the part, and

$$MAT = \{m\_id, m\_dens, m\_E, m\_ems, m\_manu\}, \tag{22}$$

where MAT is the material, m_id represents the unique identification of the material, m_dens is the density, m_E is the elastic modulus, m_ems is the waste produced by the production of this unit of mass, and m_manu is the machinability of the material.

Structural variation based on a GA

In this study, a GA is selected as a variation algorithm, and the specific process is as follows:

Code: Complete coding involves the physical structure and coding structure of the genome, which together determine the phenotype of the gene.

Set the operating parameters: The crossover factor is set to (0.4, 0.99); variation factor is set to (0.0001, 0.1); population size is set to (100, 200); and number of iterations is set to 120. Different evolutionary approaches use various genetic manipulations.

Generate the initial population: The Rand function in MATLAB generates individuals randomly as the initial population.

Fitness function: The measure of individual fitness is the fitness function. The better the fitness of individuals, the more likely they are to be retained. To ensure that fitness is a non-negative value, the following two methods are usually used to construct the fitness function:

$$F(x)=\begin{cases}C_{max}-f(x), & f(x)\le C_{max}\\ 0. & else\end{cases} \tag{23}$$

$$F(x)=\begin{cases}C_{min}+f(x), & f(x)+C_{max}\geqslant 0\\ 0. & else\end{cases}, \tag{24}$$

where C_{min} is the minimum value of the current GA, C_{max} is the maximum value of the current GA, $F(x)$ is the fitness function, and $f(x)$ is the objective function.

Product variation improvement aims to improve the product's environmental performance; hence, the objective function $Q=\sum_{i=1}^{n}x_i f_i$ is constructed as the fitness function, where x_i is the number of evolutionary structures, and f_i is the influencing factor of the evolutionary structure and environmental performance.

Terminating evolution: In this study, the termination of evolution is selected in the 120th generation. After the above steps, the product structure variation map is finally generated. The schematic diagram is shown in Figure 3.

CASE STUDY

As shown in Figure 4, there are two common types of transmission shells, and there are some structural differences in the details between the two shells.

Structural similarity analysis

First, it is necessary to refine the structure of transmission shells A and B. The results of structural refinement are shown in Tables 4 and 5, respectively.

Assume that the corresponding structures of the two transmissions A and B constitute similar elements: u_1, u_2,…,u_{10}; the degrees of influence d of each similar element value are equal. According to formula 9, the values of similar elements of corresponding structures are calculated as shown in Table 6.

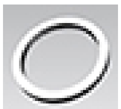
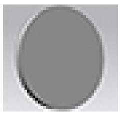
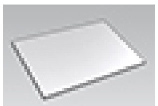
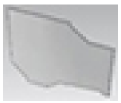
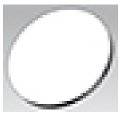
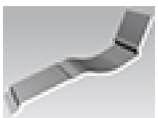
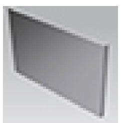
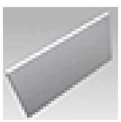
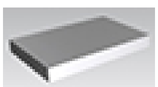
Structural common feature extraction

According to Section "2.2.1", the common features of transmission shells A and B are extracted, and the results are shown in Table 7.

Quantitative analysis of the environmental performance of the common structures

According to Section "2.3", the environmental performance of the common structures is quantitatively analyzed, and the results are shown in Table 8.

Table 4. Structure table for transmission shell A

Structural unit	Definition	Parameters	Structure	Feature collections
	Upper panel ring (AS1)	Radius of outer circle is 45 mm; thickness is 8 mm; width is 8 mm; material is steel; weight is 0.129 kg	Ring structure	A1 = (45, 8, 8)
	Left panel platform 1 (Removal structure) (AS2)	Radius is 40 mm; thickness is 8 mm; material is steel weight is 0.316 kg	Block structure	A2 = (40, 8)
	Back-wall panel (AS3)	Length, width and height: 296, 196, 8 mm; material is steel; weight is 3.643 kg	Plate structure	A3 = (296, 196, 8)
	Left and right panels (AS4)	The left side is 285 mm; right side is 212 mm; top side length is 342 mm; thickness is 8 mm; material is steel; weight is 8.054 kg	Plate structure	A4 = (285, 212, 320, 8)
	Left panel platform 2 (Removal structure) (AS5)	Radius is 30 mm; thickness is 5 mm; material is steel weight is 0.178 kg	Block structure	A5 = (30, 8)
	Lower panel (AS6)	Length, width and height: 512, 196, 8 mm; material is steel; weight is 9.85 kg	Plate structure	A6 = (512, 196, 8)
	Upper panel (Removal structure) (AS7)	Length, width and height: 326, 202, 12 mm; material is steel; weight is 6.203 kg	Plate structure	A7 = (326, 202, 12)
	Upper panel 1 (AS8)	Length, width and height: 196, 110, 8 mm; material is steel; weight is 1.354 kg	Plate structure	A8 = (196, 110, 8)
	Upper panel 2 (AS9)	Length, width and height: 178, 119, 20 mm; material is steel; weight is 3.326 kg	Plate structure	A9 = (178, 119, 20)
	Left irregular panel (Removal structure) (AS10)	Thickness is 8 mm; material is steel; weight is 3.177 kg	Plate structure	A10 = (8)
	Front panel (Removal structure) (AS11)	Length, width and height: 205, 178, 10 mm; material is steel; weight is 3.177 kg	Plate structure	A11 = (205, 178, 10)

Judgment of the inheritability of the product structure

According to the judgment method in Section "2.1", the conclusion is that the common structures of U_3, U_7, and U_8 can be inherited. If the common structures need to be improved in the future, only U_1, U_2, and U_{10} need to be improved. The remaining non-commonality structures need to be enhanced separately.

Table 5. Structure table for transmission shell B

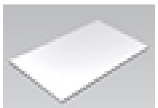
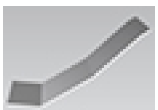
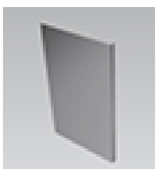
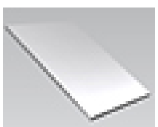
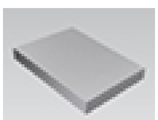
Structural unit	Definition	Parameters	Structure	Feature collections
	Upper panel ring (BS1)	Radius of tangential circle is 45 mm; thickness is 6 mm; width is 8 mm; material is steel; weight is 0.114 kg	Ring structure	B1 = (45, 6, 8)
	Left panel platform 1 (Removal structure) (BS2)	Radius is 64 mm; thickness is 7.6 mm; material is steel; weight is 0.768 kg	Block structure	B2 = (64, 7.6)
	Back-wall panel (BS3)	Length, width and height: 296, 196, 7.6 mm; material is steel; weight is 3.461 kg	Plate structure	B3 = (296, 196, 7.6)
	Left and right panels (BS4)	The left side is 307 mm; right side length is 232 mm; top side is 320 mm; thickness is 7.6 mm; material is steel; weight is 9.142 kg	Plate structure	B4 = (307, 232, 320, 7.6)
	Left panel platform 2 (Removal structure) (BS5)	Radius is 60 mm; thickness is 7.6 mm; material is steel; weight is 0.675 kg	Block structure	B5 = (60, 7.6)
	Lower panel (BS6)	Length, width and height: 544, 218, 7.6 mm; material is steel; weight is 9.104 kg	Plate structure	B6 = (544, 218, 7.6)
	Upper panel (Removal structure) (BS7)	Length, width and height: 320, 218, 16 mm; material is steel; weight is 8.762 kg	Plate structure	B7 = (320, 218, 16)
	Upper panel 1 (BS8)	Length, width and height: 202, 110, 7.6 mm; material is steel; weight is 1.326 kg	Plate structure	B8 = (202, 110, 7.6)
	Upper panel 2 (BS9)	Length, width and height: 140, 110, 28 mm; material is steel; weight is 3.385 kg	Plate structure	B9 = (140, 110, 28)
	Left irregular panel (Removal structure) (BS10)	Thickness is 7.6 mm; steel; weight is 3.018 kg	Plate structure	B10 = (7.6)
	Front panel (Removal structure) (BS11)	Length, width and height: 176, 160, 15 mm; material is steel; weight is 3.316 kg	Plate structure	B11 = (176, 160, 15)

Table 6. Values of similar elements of corresponding structures

Similar element	Value	Similar element	Value
$q(u_1)$	0.943	$q(u_7)$	0.929
$q(u_2)$	0.924	$q(u_8)$	0.982
$q(u_3)$	0.998	$q(u_9)$	0.875
$q(u_4)$	0.826	$q(u_{10})$	0.984
$q(u_5)$	0.871	$q(u_{11})$	0.813
$q(u_6)$	0.872		

Table 7. Common features of transmission shells A and B

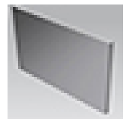
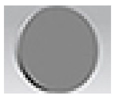
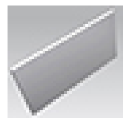
Similarity unit	Definition	Structure	Similarity unit	Definition	Structure
U1	Ring structure		U7	Plate structure	
U2	Block structure		U8	Plate structure	
U3	Plate structure		U10	Plate structure	

Table 8. Quantitative results of environmental performance

Index	Unit					
	U_1	U_2	U_3	U_7	U_8	U_{10}
Disassembly performance	2.26	2.02	4.54	4.23	4.26	2.15
Recycling performance	2.27	1.95	4.62	4.02	4.15	2.12
Toxic substances content	5	5	9	7	7	5

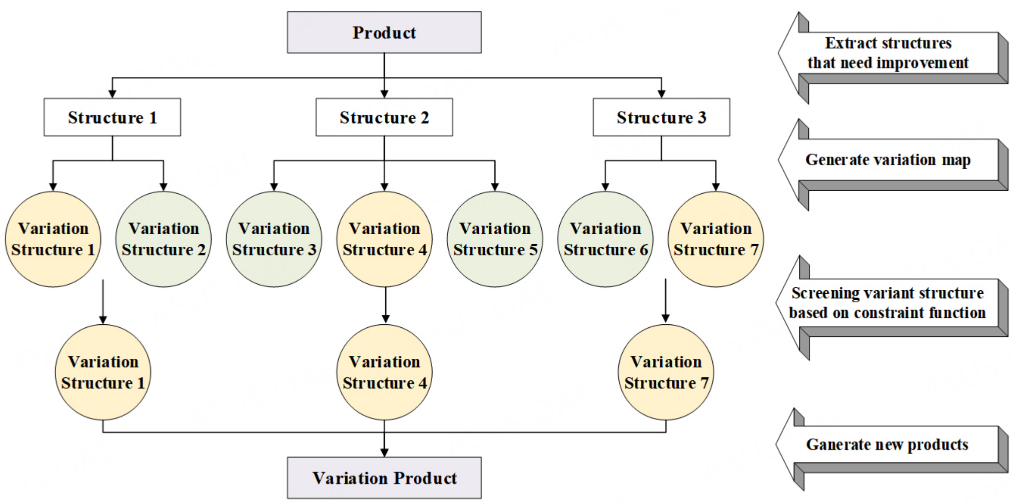
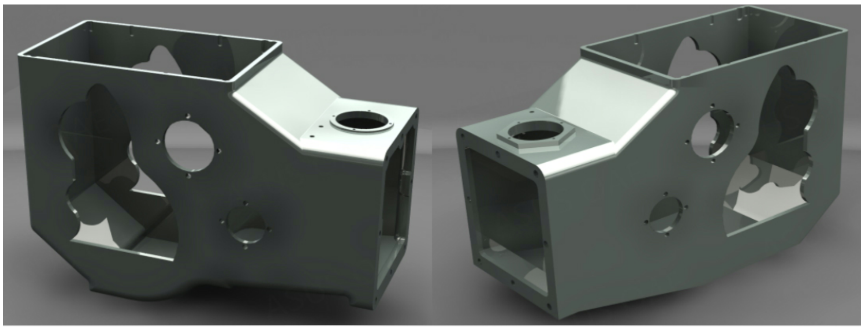


Figure 3. Schematic diagram of structural variation map generation.



(A) Appearance of type A transmission shell (B) Appearance of type B transmission shell

Figure 4. Two types of transmission shell models A and B.

Hierarchical mapping of CERs to structures

Transformation from CERs to environmental performance

After collection and analysis, the customer's initial environmental requirement set is {low toxicity, less material consumption, easy to recycle, high-cost performance, easy disassembly, low energy consumption}. The importance of CRs is determined using FAHP, as shown in Table 9. Then the QFDE house of quality is constructed to determine the environmental performance weight.

The priority relation matrix F and the fuzzy consistency matrix W are obtained using the fuzzy consistency processing of CRs:

$$F = \begin{bmatrix} 0.5 & 0.4 & 0.3 & 0.3 & 0.2 & 0.1 \\ 0.6 & 0.5 & 0.4 & 0.4 & 0.3 & 0.2 \\ 0.7 & 0.6 & 0.5 & 0.5 & 0.4 & 0.3 \\ 0.7 & 0.6 & 0.5 & 0.5 & 0.4 & 0.3 \\ 0.8 & 0.7 & 0.6 & 0.6 & 0.5 & 0.4 \\ 0.9 & 0.8 & 0.7 & 0.7 & 0.6 & 0.5 \end{bmatrix}$$

$$W = \begin{bmatrix} 0.50 & 0.45 & 0.40 & 0.40 & 0.35 & 0.30 \\ 0.55 & 0.50 & 0.45 & 0.45 & 0.40 & 0.35 \\ 0.60 & 0.55 & 0.50 & 0.50 & 0.45 & 0.40 \\ 0.60 & 0.55 & 0.50 & 0.50 & 0.45 & 0.40 \\ 0.65 & 0.60 & 0.55 & 0.55 & 0.50 & 0.45 \\ 0.70 & 0.65 & 0.60 & 0.60 & 0.55 & 0.50 \end{bmatrix}$$

The importance of the CERs can be obtained by normalization. They are 0.127, 0.147, 0.167, 0.167, 0.187, and 0.207, respectively.

Table 9. Environmental requirements of customer A

Customer requirements	Low toxicity	Less material consumption	Easy to recycle	High cost performance	Easy to disassemble	Low energy consumption
Score	1	3	5	5	7	9

Based on the importance of CERs, the house of quality for the transmission shell is established, and the corresponding environmental performance weights are calculated. (0, 1, 3, 5) denotes the degree of correlation between CERs and environmental performance weights, where 1 means unrelated, 2 means weakly correlated, 3 means generally correlated, and 4 means strongly correlated. The transformation of CERs to environmental performance weights is established, and its house of quality is shown in Table 10.

The corresponding relationship between customer A's requirement data and the environmental performance weight is obtained as follows:

$(CED,EPW) = \{(1, 3, 5, 5, 7, 9), (1.63, 2.02, 1.19, 1.13, 0.38, 2.15, 1.81, 2.79)\}$.

Taking CRs as input and the environmental performance weight as output, the sample dataset is constructed by recollecting and reorganizing data, as shown in Tables 11 and 12.

MATLAB is used to build the training model, 70% of the total data are selected as the training sample, 30% are selected as the test sample, and the sigmoid function is selected as the activation function. Model information and forecast results are shown in Table 13.

Table 13 shows that the prediction effect of this model is good. When obtaining new CRs, only model analysis is needed, and the process of building a house of quality with strong subjectivity is not needed. Therefore, subjectivity can be avoided, and the complexity of the transformation process can be reduced.

Mapping environmental performance to structures

After normalizing the weight of environmental performance, according to formula 21, the probability matrix from ecological performance to the structure of the transmission shell is calculated, as shown in Table 14.

Thus, the hierarchical mapping from CRs to structures is complete, and the probability of mapping different CRs to structures that need improvement can be obtained.

The GA requires that the gene fragments in chromosomes have the same iteration step. In this study, five gene fragments constitute the chromosome, as shown in Table 15.

Table 15 shows that the evolutionary structure is not a continuous variable; hence, the length of an interval is defined to represent a particular evolutionary structure. The interval representation of the evolutionary structure is shown in Table 15. The wall thickness of the evolutionary structure is exactly one decimal point. The wall thickness range determines the number of binary strings encoded by a single variable. Finally, the arrangement of chromosome gene segments is determined, as shown in Figure 5.

Through the GA, there are still different evolutionary modes for the structures that need to be improved. Figure 6 depicts the variation maps of the common structures U1, U2, and U10, which are not inherited.

Table 10. Customer A's house of quality for the transmission shell

CRs	Importance of CERs	Environmental performance							
		Material category	Material consumption	Parts recycle rate	Material toxicity	Toxicity of cutting fluid	Environmental properties of materials	Degree of difficulty in structural disassembly	Structural and technological properties
Low toxicity	0.127	1	0	0	5	3	3	0	1
Less material consumption	0.147	3	5	0	0	0	1	0	3
Easy to recycle	0.167	3	1	5	3	0	3	3	3
High cost performance	0.167	1	3	1	0	0	3	1	1
Easy to disassemble	0.187	1	0	1	0	0	0	5	5
Low energy consumption	0.207	1	3	0	0	0	3	1	3
Environmental performance weight	1.63	2.02	1.19	1.13	0.38	2.15	1.81	2.79	

Table 11. Sample dataset of CERs

Low toxicity	Less material consumption	Easy to recycle	High cost performance	Easy to disassemble	Low energy consumption
3.00	1.00	3.00	7.00	9.00	1.00
3.00	1.00	5.00	5.00	7.00	9.00
1.00	3.00	5.00	5.00	7.00	9.00
1.00	9.00	3.00	5.00	7.00	3.00
5.00	1.00	9.00	9.00	3.00	5.00
5.00	9.00	7.00	9.00	5.00	7.00
7.00	9.00	1.00	9.00	5.00	5.00
5.00	7.00	7.00	9.00	7.00	5.00
3.00	7.00	9.00	7.00	1.00	3.00
5.00	7.00	7.00	9.00	1.00	7.00
1.00	9.00	1.00	7.00	9.00	1.00
1.00	7.00	7.00	1.00	1.00	5.00
5.00	3.00	3.00	9.00	9.00	3.00
7.00	1.00	9.00	1.00	1.00	5.00
1.00	9.00	7.00	1.00	9.00	5.00
5.00	1.00	7.00	5.00	9.00	5.00
5.00	3.00	7.00	1.00	5.00	5.00
1.00	7.00	3.00	5.00	7.00	9.00
5.00	9.00	3.00	9.00	5.00	7.00
3.00	1.00	3.00	3.00	7.00	9.00
3.00	9.00	5.00	9.00	3.00	3.00
7.00	1.00	5.00	1.00	7.00	1.00

Table 12. Sample dataset of environmental performance

Material category	Material consumption	Parts recycling rate	Material toxicity	Toxicity of cutting fluid	Environmental properties of materials	Degree of difficulty in structural disassembly	Structural and technological Properties
1.59	1.84	1.20	1.25	0.47	2.08	1.89	2.73
1.59	1.92	1.19	1.23	0.44	2.19	1.81	2.75
1.63	2.02	1.19	1.13	0.38	2.15	1.81	2.79
1.72	2.16	1.11	1.10	0.39	2.01	1.72	2.78
1.65	1.92	1.36	1.43	0.49	2.32	1.69	2.55
1.71	2.16	1.17	1.23	0.44	2.19	1.59	2.63
1.63	2.16	0.94	1.23	0.53	2.14	1.49	2.57
1.68	2.04	1.21	1.26	0.45	2.15	1.70	2.66
1.79	2.14	1.35	1.35	0.44	2.25	1.59	2.59
1.71	2.18	1.20	1.31	0.47	2.30	1.49	2.53
1.68	2.14	1.05	1.04	0.39	1.95	1.76	2.78
1.80	2.16	1.28	1.30	0.42	2.18	1.62	2.72
1.57	1.90	1.12	1.25	0.49	2.10	1.79	2.67
1.71	1.84	1.36	1.63	0.59	2.32	1.65	2.61
1.77	2.06	1.24	1.17	0.37	1.98	1.85	2.91
1.61	1.78	1.28	1.37	0.49	2.14	1.89	2.75
1.69	1.88	1.27	1.45	0.52	2.17	1.75	2.73
1.65	2.16	1.06	1.05	0.37	2.08	1.71	2.79
1.65	2.20	1.01	1.17	0.46	2.15	1.53	2.61
1.57	1.92	1.11	1.23	0.46	2.15	1.79	2.77
1.73	2.22	1.16	1.21	0.43	2.16	1.55	2.59
1.64	1.72	1.24	1.54	0.60	2.12	1.82	2.72
1.61	2.10	0.99	1.37	0.58	2.25	1.43	2.49
1.72	1.80	1.41	1.38	0.45	2.07	1.96	2.82
1.72	1.96	1.13	1.56	0.63	2.17	1.54	2.62
1.68	2.20	1.01	1.04	0.39	2.01	1.68	2.78
1.69	1.94	1.12	1.51	0.61	2.14	1.59	2.63
1.57	1.84	1.23	1.39	0.52	2.25	1.75	2.61
1.55	1.92	1.03	1.21	0.50	2.09	1.77	2.71
1.65	1.76	1.24	1.57	0.61	2.16	1.75	2.67
1.56	1.94	1.07	1.40	0.57	2.29	1.58	2.58
1.65	1.74	1.34	1.53	0.55	2.20	1.83	2.71
1.63	2.08	1.04	1.09	0.41	2.06	1.75	2.81

Table 13. Neural network model information

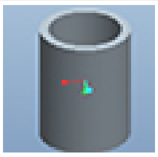
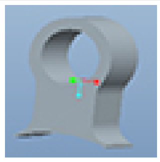
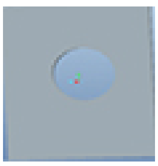
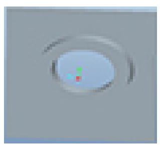
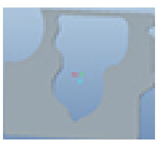
Training	Input layer	Input neurons	Hidden layer	Output layer	Output neurons	Learning rate
	CERs	130	2	Environmental performance weight	208	0.9
Testing	Input layer	Input neurons	/	Output layer	Output neurons	Maximum mean square
	CERs	42	/	Environmental performance weight	56	3.35

For different requirements, the different results of the original structures are different. After the analysis of CERs, the final constraint function Q is defined as the quality of the structures; that is, the environmental performance requirements of transmission shells are mainly concentrated on some structures with relatively

Table 14. Probability matrix from environmental performance to structures

	EP_1	EP_2	EP_3	EP_4	EP_5	EP_6	EP_7	EP_8
S_1	0.822	0.631	0.582	0.562	0.823	0	0.084	0.874
S_2	0.258	0.232	0.125	0.562	0.011	0.312	0.154	0.125
S_{10}	0	0.232	0.125	0.562	0.012	0	0	0.125
AS_4	0.312	0.894	0.882	0.562	0.415	0.215	0.268	0.235
AS_5	0.215	0.231	0.182	0.562	0.032	0.316	0.258	0.565
AS_6	0.368	0.782	0.721	0.563	0.180	0.258	0.452	0.903
AS_9	0	0.232	0.125	0.562	0.012	0	0	0.125
BS_4	0.315	0.891	0.885	0.563	0.412	0.274	0.556	0.236
BS_5	0.212	0.233	0.180	0.562	0.034	0.158	0.452	0.561
BS_6	0.365	0.784	0.723	0.560	0.182	0.268	0.368	0.901
BS_9	0	0.231	0.126	0.564	0.013	0	0	0.122

Table 15. Basic information table for the evolutionary structure

Original structure	Evolutionary structure 1	Evolutionary structure 2	
			
Binary coding	001010	011110	
			
Binary coding	001010	010100	
			
Binary coding	01010		
Material	Steel	Aluminium alloy	Magnesium alloy
density	7.85 g/cm^3	2.8 g/cm^3	1.8 g/cm^3
Binary coding	011110	010110	001010
Structure size			

Structure 1	Structure 2	Structure 3	Material	Size
000000	000000	00000	000000	00000

Figure 5. Chromosome structure.

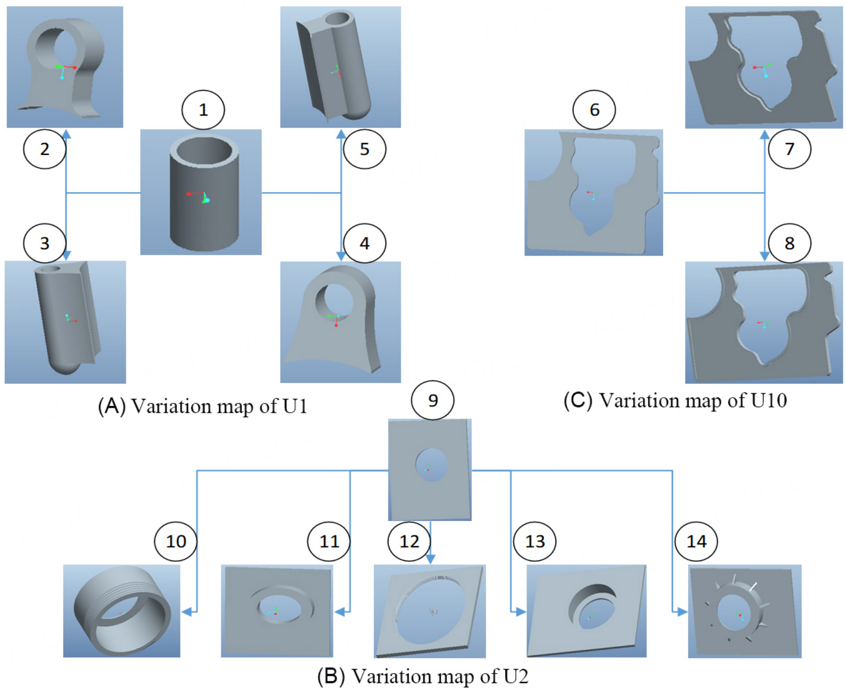


Figure 6. Product structure variation map.

large mass. High-quality structures usually have high manufacturing and use costs; hence, various structures with low mass are selected. The results are shown in Table 15, and the comparison of variation before and after is shown in Table 16.

The results in Table 17 show that the wall thickness decreased by 2.7 cm, the volume of the modified transmission increased by 905.79 cm^3, and the overall mass decreased by 27.58 kg. The environmental performance of the transmission is mainly related to its mass. Therefore, the above improvement methods effectively improve the environmental performance of the transmission.

CONCLUSION

In this study, based on structural similarity theory and the quantitative analysis of environmental performance, the concept of the inheritable structure of green products was proposed. To achieve a rapid response from CRs to the product structure, a mapping method was proposed for CRs-environmental performance weight-product structure. Combining inheritable structures and mapping methods improved the traditional product design process and shortened the design cycle. This study can provide theoretical and methodological support for carbon emission reduction in product structure design. Compared with the traditional design process, the results of this study are as follows.

(1) Based on inheritable structure theory, designers do not need to redesign all the structures when redesigning the product; they only need to consider the structures that do not satisfy CERs; hence, the workload of product redesign and the R&D cycle are reduced, and the efficiency of product redesign is improved.

Table 16. Variation structures

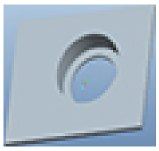
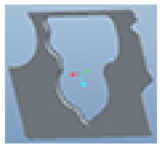
	Variation structure 1	Variation structure 2	Variation structure 3	Material	Wall thickness
Genotype	010110	001011	01011	011000	11001
Phenotype				Magnesium alloy	5.3 cm
Volume	21 cm^3	$72\pi - 25\pi\delta - \pi(6-\delta)^2 (2 - 2\delta)\ cm^3$	$-S\delta\ cm^3$		

Table 17. Comparison of parameters before and after variation

Improvement target	Before variation	After variation	Difference before and after
Wall thickness	8 cm	5.3 cm	-2.7 cm
Volume	42345.39 cm^3	43251.18 cm^3	+905.79 cm^3
Quality	37.75 kg	10.17 kg	-27.58 kg

(2) Hierarchical mapping in the process of mapping environmental performance to product structure was introduced, which effectively achieved the mapping of environmental performance to structural units.

(3) Combining four mutation operation methods (combination, decomposition, substitution, and material change) with the GA generated a product structure variation map and accelerated the generation process of improved products.

There are many issues that need to be considered in mechanical product sustainable design and it is a multi-objective decision-making problem. From the perspective of CERs, the design of products in this study is not sufficiently comprehensive. There may be more environmental requirements to consider; only typical environmental requirements were listed in this paper. Future carbon emission reduction work needs to comprehensively consider the environment, economic costs, part performance, and other factors.

DECLARATIONS

Authors' contributions

Contributed to conception and design of the study, manuscript drafting: Xuan Y
Contributed to theory and methods: Zheng Y
Contributed to data collection and analysis: Zheng C
Supervised the overall project: Li Z
Supervised the overall project: Zhang L

Availability of data and materials

Not applicable.

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

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