Product Information Modeling Based on Polychromatic Sets and Scheme Optimum Selection for Conceptual Design

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Abstract. In this paper a conceptual design product information model is established. The polychromatic sets theory was applied to this new model which was aimed at the deficiency of approach for solving product conceptual design presently. This method helps to realize the deduction from requirements to different product scheme combinations by the boolean matrixes which obtains unified colors and individual colors, the constraint relationship in the product model. To solve the conceptual design scheme evaluation problem, a decision-making method was put forward based on fuzzy analytic hierarchy process (AHP) and genetic algorithm (GA). This approach was designed to convert fuzzy information into numerical value by combining the principles of fuzzy mathematic and information axiom, and use AHP to determine the evaluation index weights. An example of vibration isolation system conceptual design was illustrated the feasibility of this method.

1. Introduction
Conceptual design is the forefront of the overall design process of the product, which has a direct impact on the subsequent design results and costs of the product. It is the focus of product design theory research. Researching on conceptual design is mainly divided into the construction of product information model to describe the conceptual design process and the reasoning based on product information model and the selection of optimal design schemes.

For conceptual design product modelling problems, Gao¹ established a conceptual design process model based on axiom design, and used the Bill Of Material (BOM) view to formalize the product concept space. Johannes et al.² used the axiom design of the polyline mapping principle to establish a conceptual design product knowledge expression model. The above research studies the formal expression of conceptual design product information from different angles, but the built-in model has insufficient integrated mapping ability for different design information in complex systems, which is not conducive to the integrated research of conceptual design and subsequent detailed design process.

For the optimization of conceptual design schemes, Tijana et al.³ solved the optimization problem of press concept design scheme by using improved ant colony algorithm. Lorenzo et al.⁴ used fuzzy analytic hierarchy process to evaluate the scheme of product concept design. The above...
research has achieved the optimization of the scheme from the qualitative or quantitative perspective, but it has not considered the conceptual design product modeling and the scheme reasoning and the evaluation of the scheme together, which is not conducive to the research of the integration of different stages of product design.

Based on the polychromatic sets set theory, this paper establishes a conceptual design product information model and uses the polychromatic sets surrounding matrix to realize the reasoning process of the conceptual design scheme. When the concept design feasible scheme is preferred, the fuzzy analytic hierarchy process is used to determine the evaluation index weight and fuzzy evaluation matrix, and the conceptual design scheme optimization model is established. Finally, the genetic algorithm is used to obtain the optimal scheme, which provides a new idea for product conceptual design modeling and optimal integration research.

2. Product conceptual design process model

It is generally believed that conceptual design refers to the workflow involved in a system that requires input as a design and output as an optimal solution. Usually, the conceptual design input function requires an output structure scheme, so it is a function-to-structure conversion process [5].

Figure 1 depicts the workflow for product conceptual design, which consists of two basic processes, synthesis and evaluation. In the comprehensive part, the total function of the system is decomposed into relatively independent sub-function units through the functional analysis, and then all the program elements that can realize the function are found. Finally, these program elements are combined to form a total program set. The evaluation part is to quantitatively evaluate the plan according to the functional indicators of the product in the obtained program set, and select the optimal plan. The synthesis part is a set of divergence generated by the design requirement reasoning, which is a divergent process; the evaluation is to select the optimal solution from the program set, which is a convergence process [6].

3. Conceptual design product modelling and scheme reasoning based on polychromatic sets

The polychromatic sets set hierarchy model is decomposed from top to bottom, and nodes are given different colors to describe their properties, parameters and other attributes. The connection relationship between nodes represents different constraint relationships, corresponding to different color edges, each edge corresponding to an inference matrix. The characteristics of the polychromatic sets set hierarchy model can describe the specific process of conceptual design products from total function decomposition to solution element implementation. The specific steps are as follows:

1) Uniform color and personal color determination. According to the product design requirements, the function decomposition is completed according to the product working process or the principle of action until it is decomposed to the lowest level function or has mature parts. Detailed definitions of

![Fig.1 Mechanical product concept design process](image-url)
the uniform color $F_i(A)$ and personal color $F_i(a)$ of each layer are in the hierarchical model. The function of the product in the $n$ layer is represented by $F_n(A)$, and the implementation method or the specific scheme is represented by $F_n(a)$, corresponding to the function $F^{n+1}(A)$ to be implemented in the next layer.

2) Constraint relationship classification and edge coloring. According to the positional relationship between functions and methods in the hierarchical decomposition structure model, the constraints are classified: $R = \{R_1, R_2, R_3, R_4\}$. Using the processing method for the constraint relationship in the polychromatic sets set, the set of edges $C$, the personal color set $F(c)$ of the edges, and the shading matrix $[C \times F(c)]$ are established.

3) The establishment of a product information model was shown in picture 2.

![Fig.2 Example of conceptual design product information model based on polychromatic sets](image)

In the polychromatic sets conceptual design process model, the connections between nodes correspond to different "color" attributes, and the coloring of edges is represented by $F_i(c)$, which corresponds to different inference or constraint matrices. If $F_i(c)=1$, it means that there is a direct reasoning relationship $R_i$ between the two vertices, which is described by matrix $[F_i(a) \times F_i(A)]$; if $F_i(c)=0$, it means that there is a direct reasoning relationship $R_i$ or $R_j$ between the two vertices, which is described by matrix $[F_i(a) \times F_i(A)]$ or matrix $[F_j(a) \times F_j(A)]$; if $F_i(c)=1$, it means that there is a direct reasoning relationship $R_i$ between the two vertices, which is described by matrix $[F_i(a) \times F_i(A)]$.

The relationship between set $F(A)$ and personal color $F(a)$ of all elements is represented by matrix $F(A) \times F(a)$:

$$
\begin{align*}
\begin{bmatrix}
F_{i1} & \cdots & F_{i2} & \cdots & F_{in}
\end{bmatrix}
\begin{bmatrix}
F(a) \\
F(A)
\end{bmatrix} = 
\begin{bmatrix}
F_1(a) \\
F_2(a) \\
\vdots \\
F_n(a)
\end{bmatrix}
\end{align*}
\tag{1}
$$

In the matrix, if $f_i \in F(a)$, then $c_{i(j)} = 1$, else $c_{i(j)} = 0$. Further, the constraint relationship between the same layers is represented by the autocorrelation matrix $[F(a) \times F(a)]$ or $[F(A) \times F(A)]$. In the process of product conceptual design, the scheme reasoning is to implement the search process from the upper-level requirement function to the lower-level function to the lower-level scheme element, and then search the constraint matrix to exclude the constraint, and finally get the product conceptual design feasible solutions sets.
4. Evaluation of conceptual design

The solution process of product concept design can be divided into two stages. The first stage is to obtain the feasible program set of the product through the analysis and reasoning of the problem, and the second stage is to evaluate the series of feasible solutions obtained.

4.1 Scheme evaluation based on fuzzy theory

In the conceptual design stage, the quantitative information of product parameters, structure, etc. are all fuzzy, so it is difficult to make evaluation decisions. The fuzzy theory is used to quantify the fuzzy information by using set and fuzzy mathematics, and the program evaluation and optimization are based on the membership degree of the product plan. High and low determination schemes have excellent grades, and preferred schemes with high grades; when scheme grades are the same, preference is given to schemes with high degree of membership.

Assume that the conceptual design to be evaluated is evaluated according to \( m \) levels, and the corresponding mathematical expression is \( V = \{v_1, v_2, \ldots, v_m\} \). The performance of the \( n \) indicators is evaluated, and the corresponding indicator set is mathematically expressed as: \( U = \{u_1, u_2, \ldots, u_n\} \). The multi-index multi-level evaluation matrix corresponding to the design scheme is as follows:

\[
R = \begin{bmatrix}
R_1 & [r_{11}, r_{12}, \ldots, r_{1j}, \ldots, r_{1m}] \\
R_2 & [r_{21}, r_{22}, \ldots, r_{2j}, \ldots, r_{2m}] \\
\vdots & \vdots & \ddots & \vdots \\
R_i & [r_{i1}, r_{i2}, \ldots, r_{ij}, \ldots, r_{im}] \\
\vdots & \vdots & \ddots & \vdots \\
R_m & [r_{m1}, r_{m2}, \ldots, r_{mj}, \ldots, r_{mm}]
\end{bmatrix}
\]

(2)

The elements in \( V \) correspond to different evaluation levels, such as \{very good, good, normal, bad,...\}; \( t_i \) indicates the degree of subordination of the product plan for the evaluation index \( u_i \) with respect to level \( v_j \).

Conceptual design scheme evaluation index weight \( W = \{w_1, w_2, \ldots, w_n\} \), among them, \( 0 < w_i < 1 \), \( \sum_{i=1}^{n} w_i = 1 \). Then the weighted fuzzy comprehensive evaluation vector is as follows

\[
B = W \times R = (b_1, b_2, \ldots, b_j, \ldots, b_m)
\]

(3)

Among them, \( b_j = \sum_{i=1}^{m} w_i t_j \) \( j \in [1,m] \) is the subordination of the \( j \) comment in the fuzzy comprehensive evaluation.

When the fuzzy theory is used to evaluate and optimize the scheme, the fuzzy evaluation of the design scheme is used to determine the superior level of the membership degree. The scheme with high grade is preferred. When the scheme level is the same, the membership degree is high.

4.2 Establish program evaluation model

Firstly, the weight of the evaluation index is determined based on the AHP method:

\( 1 \) Establish a judgment matrix based on the relative importance of each design factor in product design: \( A = [a_{ij}]_{n \times n} \)

\( 2 \) Calculate the maximum eigenvalue \( \lambda_{\text{max}} \) of \( A \) and the corresponding eigenvector \( W = (w_1, w_2, \ldots, w_n) \)

\( 3 \) Calculate \( CI \) and \( CR \), \( CI = (\lambda_{\text{max}} - n) / (n-1) ; CR = CI / RI \)

Quantify the program evaluation level \( V = \{v_1, v_2, \ldots, v_m\} \) according to the specific situation, convert it to comment vector \( Q = (q_1, q_2, \ldots, q_n) \). Each of the program elements in a series of feasible solutions obtained through the program reasoning is assigned to the expert evaluation to determine the respective comprehensive evaluation vectors \( R \). Calculate the comprehensive evaluation vector \( B \) of
each component according to the weight vector $W$ of each evaluation index $[7]$. Then the comprehensive evaluation score for each component is as follows:

$$c = Q \cdot B = \sum_{j=1}^{m} q_j b_j$$  \hspace{1cm} (4)$$

The choice of the conceptual design is transformed into the component combination of the constituents, and the objective function is determined as:

$$\text{max} \ y = \sum_{i=1}^{n} \sum_{j=1}^{m_i} c_{ij} u_{ij}$$  \hspace{1cm} (5)$$

$c_{ij}$ is the evaluation score of the selected component. $u_{ij}$ indicates the $j$ component of the $i$ module, if $u_{ij} = 1$, it includes the component, $u_{ij} = 0$ indicates that it is not included.

4.3 Solution of Scheme Evaluation Model Based on Genetic Algorithm

(1) Determination of chromosome coding method

The design of the coding scheme is based on the idea of gene expression, using a binary multi-parameter cascade coding method. When the product can achieve a certain function or have a certain structure, it is represented by gene 1; otherwise, it is represented by 0. When the product concept is designed, it is broken down into different modules according to functions. The structure of each module is a gene segment. The chromosome length of each module is the number of components that meet the requirements. Each module can only select one mechanism. Therefore, each segment can only have one gene value of 1, and all other gene values are 0.

(2) Determination of fitness function

Determine the fitness function of the algorithm according to the objective function:

$$f_i = \frac{y_i}{\sum_{j=1}^{N} y_j}$$  \hspace{1cm} (6)$$

Among them, $N$ is the size of the initial population, $y_i$ is the fitness value of the $i$ individual.

(3) Determination of algorithm control parameters

Determine the population size of the algorithm $N$, the number of iterations of the algorithm $M$, the probability of crossover $P_c$, and the probability of mutation $P_m$.

The flow of using the fuzzy genetic algorithm to optimize the design scheme is shown in Figure 3.
Fig. 3 Algorithm implementation flow chart

5. Instance application
Take the conceptual design of the vibration isolation system as an example. The known user requirements are: passive vibration isolation system, complex structure, high requirements for high-frequency vibration isolation performance, low equipment centroid position, minimum vibration frequency required to be isolated, high temperature resistance and oil resistance are not required.

5.1 Polychromatic sets modeling of vibration isolation system
Figure 4 is a functional decomposition hierarchical structure model of the vibration isolation system design, in which the dotted line indicates the selection constraint of the vibration isolation component by the support mode, and the thick solid line indicates the selection constraint of the support mode component element to the vibration isolation component scheme element.

Fig. 4 Vibration isolation system conceptual design model
In Fig.4, The 0th layer represents the user's design requirements for the vibration isolation product 

\[ F(A(0,0,0)) = F_0^1 F_2^0 \cdots F_{14}^0, \]

Functional characteristics of the first layer of vibration isolation products 

\[ F(A(1,1,0)) = F_1^1 F_2^1 F_3^1 F_4^1, \quad F(A(1,2,0)) = F_6^1 F_7^1 \cdots F_{10}^1; \]

The method set corresponding to the second layer support mode is 

\[ A(1,1,0) = a_1 a_2 a_3 a_4 a_5, \]

The method set corresponding to the vibration isolating component is 

\[ A(1,2,0) = a_1 a_2 \cdots a_{21}. \]

5.2 Vibration isolation system scheme reasoning
There are six edges in the hierarchical structure model of the vibration isolation system, which correspond to three kinds of constraint relationships. Each edge has a corresponding reasoning or
constraint matrix. For the first type of direct reasoning relationship $R_i$, corresponding edge color $F_i(c) = 1$, as $[F(a) \times F(A)]$ and $[F(A) \times F(A)]$ establish an inference matrix, as follows:

$$T_i = [F(A(1,1,0)) \times F(A(0,0,0)); A(0,0,0)]$$

As can be seen from Fig5, $A(1,1,0)$ and $A(1,2,0)$ contain the second type of constraint $R_2$ represented by matrix $F(a) \times F(a)$. $F(A(1,1,0))$ and $A(1,2,0)$ contain the second type of constraint $R_3$, represented by matrix $F(A) \times F(A)$ as follows:

$$S_1 = [A(1,2,0) \times A(1,1,0)]$$

$$S_2 = [A(1,2,0) \times F(A(1,1,0))]$$

Fig.5 is a polychromatic sets surrounding matrix that characterizes the constraint relationship in the design of vibration isolation system.

According to the reasoning matrix $T_i$, the following two design schemes are obtained, which are represented by polychromatic sets lanes as follows:

For scheme 1, according to the reasoning matrix $T_3, T_4$, four design scheme combinations can be obtained: $(a_2, a_{16}), (a_2, a_{16}), (a_1, a_{16}), (a_1, a_{16})$; For scheme 2, 6 design scheme combinations can be got: $(a_2, a_{16}), (a_2, a_{16}), (a_2, a_{16}), (a_1, a_{16}), (a_1, a_{16}), (a_1, a_{16})$. According to the constraint matrix $S_1, S_2$, it can be seen that the constraints of the scheme $(a_2, a_{16})$ and the scheme $(a_2, a_{16})$ cannot be realized in reality, and finally eight feasible schemes are obtained: $(a_2, a_{16}), (a_2, a_{16}), (a_1, a_{16}), (a_1, a_{16}), (a_1, a_{16}), (a_1, a_{16}), (a_1, a_{16}), (a_1, a_{16})$.

5.3 Vibration isolation system evaluation

(1) Determine weight

Firstly, comprehensively evaluate the design factors of the vibration isolation system considering mechanical performance, economy, system maintainability and versatility, and score the design factors
importance judgment matrix by experts.

\[
E = \begin{bmatrix}
1 & 2 & 2 & 1 \\
1/2 & 1 & 1 & 1/2 \\
1/2 & 1 & 1 & 1/2 \\
1 & 2 & 2 & 1
\end{bmatrix}
\] (7)

Then calculate the maximum eigenvalue of \(E\) as \(\lambda_{\max} = 4.001\), \(CI = \frac{\lambda_{\max} - n}{n - 1} = 0.0007\), look up the table \(RI = 0.9\), so that: \(CI / RI = 0.0007 < 0.1\), Compliance with conformance testing standards. Finally, the weight vector of the evaluation index of the conceptual design of the vibration isolation system is obtained by normalizing the feature vector:

\[
W = (0.333, 0.167, 0.167, 0.333)
\]

(2) Fuzzy comprehensive evaluation of scheme elements

For vibration isolation system, comment set: \(V = \{v_1, v_2, v_3, \ldots, v_n\}\),\{very good, good, normal, bad\}

Establish each component evaluation matrix \(R\) based on the membership of the four components of mechanical performance, economy, system maintainability and product versatility:

\[
R = \begin{bmatrix}
R_1 & R_2 & R_3 & R_4 \\
\end{bmatrix}
\] (8)

The weighted evaluation indicator vector becomes:

\[
B = W \cdot R = (b_1 b_2 b_3 b_4)
\] (9)

Table 1 shows the membership of the 21 components of the vibration isolation system to the above four evaluation indicators:

| V1 | V2 | V3 | V4 | V5 | V6 | V7 | V8 | V9 | V10 |
|----|----|----|----|----|----|----|----|----|-----|
| 61 | 0.39 | 0.52 | 0.15 | 0.44 | 0.38 | 0.20 | 0.24 | 0.11 | 0.29 | 0.50 |
| 62 | 0.10 | 0.30 | 0.32 | 0.14 | 0.13 | 0.41 | 0.24 | 0.30 | 0.19 | 0.18 |
| 63 | 0.15 | 0.13 | 0.17 | 0.23 | 0.19 | 0.14 | 0.31 | 0.30 | 0.27 | 0.17 |
| 64 | 0.36 | 0.05 | 0.36 | 0.19 | 0.30 | 0.22 | 0.21 | 0.29 | 0.25 | 0.15 |

Table 1 Comprehensive evaluation table for each component

| V11 | V12 | V13 | V14 | V15 | V16 | V17 | V18 | V19 | V20 | V21 |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 61  | 0.32 | 0.41 | 0.37 | 0.44 | 0.37 | 0.34 | 0.32 | 0.23 | 0.36 | 0.27 | 0.34 |
| 62  | 0.21 | 0.18 | 0.24 | 0.27 | 0.24 | 0.28 | 0.26 | 0.27 | 0.18 | 0.28 | 0.19 |
| 63  | 0.19 | 0.13 | 0.26 | 0.20 | 0.26 | 0.21 | 0.17 | 0.16 | 0.27 | 0.16 | 0.27 |
| 64  | 0.28 | 0.28 | 0.13 | 0.09 | 0.13 | 0.17 | 0.25 | 0.34 | 0.19 | 0.29 | 0.20 |

(3) Scheme optimization based on genetic algorithm

The design of the vibration isolation system is quantified, and the corresponding vector after quantization is as follows:

\[
Q = (q_1, q_2, q_3, q_4) = (10, 7, 5, 2)
\] (10)

The vibration isolation system is composed of two parts: the supporting method and the corresponding component of the vibration isolating component. The corresponding conceptual design optimization model is as follows:

\[
y = \max \sum_{j=1}^{4} q_j x_j + \max \sum_{j=1}^{4} q_j x_j (\ell \in [1,6]; j \in [7,21])
\]

\[
s_j (x_j \neq 0) \cup (x_i \neq 0)
\] (11)

Among them, \(x_i\) is the degree of membership of evaluation component \(j\) for vibration isolation scheme component \(i\). The fitness function of the algorithm is shown in Equation (6).

The parameters of the algorithm are set as follows: binary encoding, The population size is 10 and
the maximum number of iterations is 100, $p_c = 0.8$, $p_m = 0.1$. The optimal combination scheme calculated by calculation is $(a_2, a_4)$, its corresponding target value is 15.52. The optimal value curve and the average fitness convergence curve during the running of the algorithm are shown in Fig. 6.

Fig. 6 Convergence curve of genetic algorithm

It can be seen that the first group of schemes is the optimal design scheme, and the high-level support 1 is used as the support mode. The spring and the rubber are connected in parallel as the support scheme element. The vibration isolation scheme has good design mechanical performance. The high support mode 1 is nested in the external mass base through the inner mass, which can realize the lateral limit brake well, prevent lateral vibration slip and improve stability. The spring and the rubber are arranged in parallel, and the vibration isolation effect is better. The specific structure diagram is shown in Fig. 7.

Fig. 7 Vibration scheme system conceptual design optimal scheme structure diagram

6. Conclusion

In this paper, the polychromatic sets set theory is used to establish the product conceptual design information model. The concept of unified color and individual color in polychromatic sets set is used to establish the inference and constraint matrix to describe the complex constraint relationship in the model. The model is more conducive to computer expression. For the solution of the conceptual design scheme, firstly, the feasible design set of product design is obtained by searching the
polychromatic sets set surrounding matrix from top to bottom, and the solution space is reduced. The fuzzy evaluation matrix is established by using fuzzy theory, and the weight of the evaluation index of the scheme is determined by AHP method. The scheme evaluation model is established and the optimal scheme combination is solved by genetic algorithm. Taking the conceptual design of vibration isolation system as an example, the product information model of vibration isolation system and the corresponding reasoning and constraint matrix are established. By searching the surrounding matrix, the feasible scheme of vibration isolation system design is obtained. The fuzzy theory, analytic hierarchy process and genetic algorithm are used to obtain the optimal combination of vibration isolation system, which shows that the conceptual design idea proposed in the paper is feasible.

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