Research for aircraft design process optimization based on design structure matrix

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Abstract. The interaction of information during the structural design of aircraft is complex. In order to optimize the design process and improve the efficiency in research and development, this paper performs clustering calculation on the structural design matrix of a certain type of trainer and optimizes it through genetic algorithm. In addition, a specific method for calculating the amount of information through information connection weight is given. The simulation results show that the optimized matrix has strengthened the information interaction within the cluster, reduced the information interaction between clusters, and reduced the frequency of information feedback during the design process, which plays a role in improving the efficiency of research and development.

1. Introduction

The structural design of the aircraft has high complexity and strong coupling, and there is more information output and feedback. If a problem occurs in one link of the design process, it will cause correction and rework in other links, thus delaying the research and development cycle. Therefore, if clustering calculation is carried out for the design process, the closely related links will be grouped into one category, which will effectively reduce the intensity of information interaction between clusters, thus improving research and development efficiency and shortening research and development cycle[1].

The design structure matrix (DSM) can clearly indicate the interaction between the elements, and it has outstanding advantages in complex projects[2]–[4]. By optimizing DSM, the complexity of the system can be effectively reduced. At present, DSM has less research and application in aerospace field, but there has been many researches in ship design, architectural assembly and business processes. Deng[5] et al. proposed a new segmentation algorithm based on DSM to optimize the ship design plan, eliminate the unreasonable part of the plan and improve the design efficiency. Zhao[6] et al. used DSM to model and analyze the construction methods of prefabricated buildings, and proved that DSM can solve the problems of overlap and iteration in the construction process, thereby significantly reducing the risk of rework and shortening the construction cycle. Yuan[7] et al. apply DSM to topological sorting in business processes, which has a good effect compared with traditional topological sorting.

This research will analyze the structure design process of a certain type of trainer and establish a design structure matrix based on the information connection weight. Then we use clustering
calculation to reconstruct the design structure matrix, and adopt genetic algorithm to optimize it, so as to optimize the design process.

2. Implementation

In this section, three parts are introduced: 1. The modeling method of the fuselage design process of a certain type of trainer aircraft. 2. Clustering method of design elements and coding rules of DSM. 3. A method to calculate the amount of information based on information connection weights

2.1. Modeling

Design structure matrix is a method introduced by Donald Steward in 1981 for information flow analysis[8]. It is used to display the interaction of various elements in the matrix, which is conducive to visual analysis of complex projects. The row and column elements represent activities in the design process, and the row and column elements are arranged in the same order. The cells in the matrix represent the relationship between the corresponding row and column elements. The diagonal elements represent the task itself, the elements below the diagonal line indicate the output of information, and the diagonally divided elements indicate the feedback of the information.

Design structure matrix can be divided into numerical matrix and Boolean matrix. In this paper, we intend to use a numerical matrix modeling method to establish the matrix of the design process. The values in the matrix represent the information connection weight between the two elements. Through consulting experts, the design structure matrix of the rear fuselage of a certain type of training aircraft is shown in Table 1. Number 1-3 represent low contact strength, number 4-6 represent medium contact strength, and number 7-9 represent high contact strength. Through statistics, there are 21 low-strength points, 13 medium-strength points, and 60 high-strength points in the matrix.

| Table 1. DSM of the structural design of a type of trainer. |
|-----------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| Design element  | 1      | 2      | 3      | 4      | 5      | 6      | 7      | 8      | 9      | 10     | 11     | 12     | 13     | 14     | 15     | 16     | 17     | 18     | 19     | 20     | 21     | 22     | 23     |
| Overall layout design | 1 9 9 3 3 5 8 9 3 8 | 8 |
| Force transfer scheme design | 2 9 9 9 5 8 |
| Key technology determination | 3 |
| Quantity demonstration of test pieces | 4 |
| Structural scheme design | 5 9 5 9 9 9 9 |
| Structure specification | 6 3 3 3 |
| Process review | 7 5 8 3 8 9 |
| Design review | 8 5 8 3 8 9 |
| Control scheme design | 9 9 9 9 9 5 8 |
| Structural strength assessment | 10 9 9 |
| Assess the strength of the layout plan | 11 9 8 9 8 |
| Dynamic evaluation | 12 9 3 3 9 9 |
| Overall zoning coordination | 13 8 9 9 |
| Technical design of body structure | 14 3 5 3 3 3 3 |
| Mass distribution calculation | 15 5 9 9 |
| Critical component test | 16 5 9 3 9 9 |
| Control technology design | 17 3 9 3 5 8 |
| Strength calculation of system technology | 18 |
| Fatigue strength calculation | 19 8 |
| 3D model design of component | 20 8 |
| Detailed structural design | 21 8 9 9 9 9 9 |
| Structural strength calculation | 22 8 9 9 9 9 9 |
| Strength test | 23 9 9 |

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2.2. Clustering and coding

Clustering is one of several operations for DSM, and its role is to classify closely related elements in DSM[9]. Because the design process contains many design elements, and the strength and frequency of inter-element connections are complicated, the research uses a clustering algorithm based on information connection weight to reorganize the design process matrix model. The optimized DSM by clustering can effectively group the closely related design elements into the same cluster, so that the strength of the connection between design elements within the same cluster is higher, but between different clusters the strength of the connection is lower.

In this paper, we divide matrix elements into 5 categories, including 1 BUS cluster and 4 ordinary clusters. The elements in the BUS cluster have high interaction weight with other elements[10], so they should be given global attention in the design. We use number 0 to represent the BUS class, and use number 1 to 4 represent the class 1, class 2, class 3 and class 4, respectively.

The coding rules of this study are summarized as the following two steps:

Step1: Remove the independent elements in the matrix. Independent elements are elements that have no or little contact with other elements.

Step2: For the remaining elements in the matrix, each element position is randomly encoded with an integer value of [0, 1, 2, 3, 4], corresponding to different categories.

From Table 1, we can see that there is no information interaction between element 3 and other elements, so element 3 is listed as an independent element.

2.3. The amount of information based on information connection weight

In this paper, we use information quantity as the evaluation criterion of genetic algorithm. The amount of information includes the amount of information within the cluster and the amount of information between clusters. The amount of information between clusters consists of two parts: 1. The amount of information between ordinary clusters. 2. The amount of information between BUS cluster and ordinary clusters. In this study, we give a specific calculation method based on the information weight, as shown in formula (1)-(3):

\[ C_1 = \sum_{i=1}^{N-1} S_i \cdot C_i + S_{bus} \cdot C_{bus} \]  
\[ C_2 = \left\{ \begin{array}{ll} \sum_{i=1}^{N-1} \sum_{j=1}^{N-1} \alpha \cdot (S_i + S_j) \cdot C_{i,j}, & i \neq j \\ 0, & i = j \end{array} \right. \]  
\[ C_3 = \sum_{i=1}^{N-1} (S_{bus} + 1) \cdot (S_{bus} + S_i) \cdot C_{bus,i} \]

Among them, \( C_i \) represents the amount of information within the cluster, \( C_2 \) represents the amount of information between ordinary clusters, and \( C_3 \) represents the amount of information between BUS cluster and ordinary clusters. \( N \) represents the number of ordinary clusters. \( S \) represents the cluster size, which is the number of elements contained in the cluster. \( \alpha \) represents the influence coefficient of the ordinary clusters on the information flow value. \( C_i \) represents the amount of information inside the cluster, and its value is the sum of the connection weights of all the cells in the matrix constructed by the elements inside the cluster. \( C_{i,j} \) represents the amount of information between clusters, and its value is the sum of the connection weights of all cells in the dimensional matrix composed of the elements of the two clusters. So the total information volume of each individual is the summation of \( C_1, C_2 \) and \( C_3 \).

3. Simulation and comparison

3.1. Optimized by genetic algorithm

Genetic algorithm will be affected by the parameters of population size, number of iterations, crossover probability and mutation probability. Therefore, in this study, different clustering schemes are obtained by setting different parameters. The smaller the amount of information and the size of the BUS class are, it means that the matrix model has stronger internal connections among clusters and weaker connections between different clusters, and the clustering results tend to be optimal.
The parameter setting and optimization results are shown in Table 2. In the case of a population size of 100 and 1000 iterations, when the crossover probability is 0.9 and the mutation probability is 0.1, the amount of information is the smallest. Under this scheme, the BUS class size is 1. The optimization curve of this scheme is shown in Figure 1. When iterating to the 761th time, the curve has converged, and the minimum value is 5346.4. Under this scheme, the optimal individual obtained is shown in Table 3. The optimal clustering scheme obtained after decoding is as follows:

BUS: Overall layout design
Class1: Force transfer scheme design, Structural scheme design, Control scheme design, Structural strength assessment, Assess the strength of the layout plan
Class2: Overall zoning coordination, Mass distribution calculation, Technical design of body structure, Control technology design, Strength calculation of system technology
Class3: Structure specification, Fatigue strength calculation, Detailed structural design, Design review, Process review, Dynamic evaluation, Structural strength calculation
Class4: Quantity demonstration of test pieces, Strength test, Critical component test, 3D model design of component.

Table 2. Comparison of optimization results under different parameters.

| Crossover probability | Mutation probability | Value of information | Scale of BUS class |
|-----------------------|----------------------|----------------------|-------------------|
| 0.8                   | 0.1                  | 8483.0               | 2                 |
| 0.8                   | 0.05                 | 10920.2              | 2                 |
| 0.9                   | 0.1                  | 5346.4               | 1                 |
| 0.9                   | 0.05                 | 6338.8               | 1                 |

Figure 1. The optimization curve of genetic algorithm for the optimal individual.

Table 3. The coded form for the optimal individual.

| Element | 1 | 2 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 |
|---------|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| Class   | 0 | 1 | 4 | 1 | 3 | 3 | 3 | 1 | 1  | 1  | 3  | 2  | 2  | 4  | 2  | 2  | 4  | 2  | 3  | 4  | 3  | 3  | 4  |

3.2. Reconstruction and comparison of DSM

The design elements in the matrix were rearranged according to the clustering results. After adding independent element, the reconstructed matrix was obtained as shown in Table 4. Compared with
Table 1, the weights of information connection in the matrix after clustering are concentrated inside the cluster, and the information interaction between the clusters is significantly reduced. In addition, the information feedback in the matrix before and after clustering is statistically shown in Figure 2. It can be found that in the matrix after clustering, the frequency of feedback information is 35, and the frequency of high connection weight is 20. While in the original matrix, the frequency of feedback information points is 42, and the frequency of high connection weight is 25. Therefore, the clustered matrix effectively reduces the frequency of information feedback.

![Figure 2. Statistics of information feedback before and after clustering.](image)

| Design element                                      | 1 | 3 | 5 | 10 | 2 | 8 | 11 | 13 | 15 | 14 | 17 | 18 | 6 | 19 | 21 | 8 | 7 | 12 | 22 | 4 | 25 | 16 | 30 |
|-----------------------------------------------------|---|---|---|----|---|---|----|----|----|---|----|----|---|---|----|---|---|----|---|---|----|---|---|----|---|
| Key technology determination                        | 3 |   |   |    |   |   |    |    |    |   |    |    |   |   |    |   |   |    |   |   |    |   |   |    |   |
| Overall layout design                               | 1 | 9 | 5 | 9 | 8 | 9 | 3 |    |    |   |    |    |   |   |    |   |   |    |   |   |    |   |   |    |   |
| Structural scheme design                            | 5 | 9 | 5 | 9 | 8 | 9 |    |    |    |   |    |    |   |   |    |   |   |    |   |   |    |   |   |    |   |
| Structural strength assessment                      | 10| 9 | 5 | 9 |    |   |    |    |    |   |    |    |   |   |    |   |   |    |   |   |    |   |   |    |   |
| Force transfer scheme design                        | 2 | 9 | 5 | 9 |    |   |    |    |    |   |    |    |   |   |    |   |   |    |   |   |    |   |   |    |   |
| Control scheme design                               | 9 | 9 | 5 | 9 |    |   |    |    |    |   |    |    |   |   |    |   |   |    |   |   |    |   |   |    |   |
| Assess the strength of the layout plan              | 11| 9 | 9 | 5 |    |   |    |    |    |   |    |    |   |   |    |   |   |    |   |   |    |   |   |    |   |
| Overall zoning coordination                         | 13| 9 | 5 |    |   |    |    |    |    |   |    |    |   |   |    |   |   |    |   |   |    |   |   |    |   |
| Mass distribution calculation                       | 15| 9 | 5 |    |   |    |    |    |    |   |    |    |   |   |    |   |   |    |   |   |    |   |   |    |   |
| Technical design of body structure                  | 14| 9 | 5 | 5 | 9 | 8 |    |    |    |   |    |    |   |   |    |   |   |    |   |   |    |   |   |    |   |
| Control technology design                           | 17| 9 | 5 |    |   |    |    |    |    |   |    |    |   |   |    |   |   |    |   |   |    |   |   |    |   |
| Strength calculation of system technology           | 18| 9 | 5 |    |   |    |    |    |    |   |    |    |   |   |    |   |   |    |   |   |    |   |   |    |   |
| Structure specification                             | 6 | 9 | 5 |    |   |    |    |    |    |   |    |    |   |   |    |   |   |    |   |   |    |   |   |    |   |
| Fatigue strength calculation                        | 19| 9 | 5 |    |   |    |    |    |    |   |    |    |   |   |    |   |   |    |   |   |    |   |   |    |   |
| Detailed structural design                          | 21| 9 | 5 |    |   |    |    |    |    |   |    |    |   |   |    |   |   |    |   |   |    |   |   |    |   |
| Design review                                       | 8 | 9 | 5 | 9 |    |   |    |    |    |   |    |    |   |   |    |   |   |    |   |   |    |   |   |    |   |
| Process review                                      | 7 | 9 | 5 |    |   |    |    |    |    |   |    |    |   |   |    |   |   |    |   |   |    |   |   |    |   |
| Dynamic evaluation                                  | 12| 9 | 5 |    |   |    |    |    |    |   |    |    |   |   |    |   |   |    |   |   |    |   |   |    |   |
| Structural strength calculation                     | 22| 9 | 5 |    |   |    |    |    |    |   |    |    |   |   |    |   |   |    |   |   |    |   |   |    |   |
| Quantity demonstration of test pieces              | 4 | 3 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 3 | 3 | 3 | 3 | 3 | 9 | 9 | 3 | 3 | 3 | 3 | 3 | 3 |
| Strength test                                       | 3 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 |
| Critical component test                             | 16| 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 |
| 3D model design of component                        | 3 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 |

Table 4. DSM after clustering optimization for structural design of a type of trainer.
4. Conclusion

In this paper, we propose a specific method for calculating the amount of information based on information connection weights. By clustering calculation and optimization of the design process matrix of a certain type of trainer, the best clustering scheme is obtained, and the DSM is reconstructed according to the clustering results. By comparison, it is found that the reconstructed matrix effectively enhances the information interaction within the cluster and reduces the information feedback intensity, thus improving the research and development efficiency.

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