Classification and Unified Expression of General Aircraft Product Functions

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Abstract: With the continuous progress of The Times, the complexity and innovation of products in the design and manufacturing process are gradually increasing. Because of the interdependence and coupling between the composition or function of complex products, the product development cycle is greatly extended, and the problem of low reuse in the design process is also caused. This paper aims at the problems of product function coupling, iteration and reuse. By analyzing the design status of domestic complex products and adopting the combination of black box model, complex network model and GA genetic algorithm. The model of product function classification and unified expression is put forward. Finally, the helicopter engine power plant is taken as an example to demonstrate. It helps demonstrating the validity of the research and provides an effective reference for the design of general aircraft product functions.

Keywords: **Complex Product; Design Reuse Degree; Black Box Model; Complex Network; Genetic Algorithm; General Aircraft**

1. Introduction

1.1 Research Background and Significance

Complex products refer to high-end equipment with large product structure, high research and development cost, complex development process and long development cycle [1]. Complex products are usually composed of multiple components and functions, and there is a coupling relationship between them. This coupling relationship means that a change in one component or function may have an impact on other components or functions, so that the overall performance of the product is affected. This coupling relationship can cause the following problems:

(1)Function iteration problem: When a certain function of the product needs to be modified or updated, the whole product may need to be redesigned or modified due to the coupling relationship between the functions. It will lead to the extension of the product development cycle and affect the market competitiveness of the product.

(2)Design reuse problem: During the development of complex products, there may be multiple components or functions that can be reused. However, due to the coupling relationship between them. This increases the cost and time of development.

General aircraft as a complex product, its types are constantly enriched, there are significant structural differences between products. At the same time, as a complex product, the development and manufacturing process of aviation products is a coordinated process among multiple departments, involving rich and diverse information resources. There is interdependence and coupling between various elements within the system, which is manifested as the interaction of matter, energy, and signal. Therefore, aiming at the problem of how to improve the function reuse degree of product series, this paper proposed the division of product function modules based on the complex product function network modeling and genetic algorithm, and took general aircraft as an example to provide reference for improving the function reuse degree of product design.

1.2 Domestic Research Status

1.2.1 Research status of complex product design

In the process of product design, modular design presents a wide range of applications, including design, production, maintenance, recycling and other. This design form has a positive significance for realizing the green manufacturing of products and improving the comprehensive value [2]. However, in the actual design process, the same function in the product series uses different parts structure and parameter design, resulting in the problem of low reuse, which will make the development management process more complicated and hinder the improvement of product standardization.

Based on the product family disassembly design study, Yang Lin integrated two sustainable modularity drivers for disassembly design, namely material similarity and life similarity, but no product functional modularity [3]. Salhieh presents a systematic framework that can capture the functional requirements and functional-structure mapping based on users' requirements [4]. However, Xiao Renbin proposed a method to establish a new product platform, which is based on the functional structure mapping matrix, and doesn't propose a platform scheme to promote the reuse of product functions [5]. Zhu Bin proposes the mapping relationship and product bill of materials based on the axiomatic design to analyze product structure and construction but doesn't delve into how to improve the reuse rate of product functions [6].

In the field of product design, based on the "product development innovation is mostly reuse the existing design knowledge and design principle, essentially with the thoughts and laws of biological genetic information" [7], such as Li Ting's [8] research is based on a hybrid ant colony algorithm to optimize the propagation path of product design changes, with the goal of minimizing the propagation intensity of changes and obtaining the optimal propagation path of changes.

Studies have pointed out that complex products usually form complex networks due to the internal coupling, which can affect the modular effect. Using the modular method is an effective way to solve the problem of coupling between systems, and to solve the different forms of coupling relationship between systems by constructing the modular structure with low coupling in the system and high aggregation in the system.

1.2.2 Research status of general aircraft design

Domestic research on general aircraft mainly focuses on the maintenance of general aircraft products and the optimization of specific product functions. Wang [9] studied the design of integrated business subsystem based on workflow and rule engine, and realized the business information management of general aviation flight service. Dong Shipeng [10] provided a semi-differential control mechanism for miniaturized coaxial helicopter, and innovatively changes the lift change caused by semi-differential direction control from the total distance compensation to the rotor speed change, thereby reducing the weight, Xiang [11] proposed a multi-objective optimization mathematical model with the helicopter flight endurance time and the quality of the power system cost.

The modularity of functional structure by traditional methods mainly relies on qualitative analysis of functional flow, lacking the studies of quantification and directionality of functional flow intensity, which brings adverse effects on the subsequent design. Therefore, it is of great significance for aircraft manufacturers to study the modular classification of general aircraft products and to improve the reuse degree of general aircraft products.

1.3 Research Content and Technical Route

The research ideas of this paper are as follows: First, it summarizes the research background and the research status at home and abroad, emphasizing the importance and innovation of realizing the function reuse of complex products. Next, we analyze the problem types leading to the low reuse degree of product function and explain the theoretical basis based on the complex network and genetic algorithm. Finally, the engineering feasibility and effectiveness of the theory are verified through the actual case of general aircraft.

1.3.1 Establish the product function model based on the black box model

The total function of the product is decomposed to form several interrelated sub-function systems, using the black box model, including the total function and the input / output function flow. Considering the position of each functional flow, the sub-function of the total function is derived into the black box model for output and establish the product functional structure model.

1.3.2 Establish a functional network structure model

After the function of the product system, map the functional bases into network nodes, and the connection between sub-functions is represented with directed edges, and the weight of the edges represents the comprehensive strength of sub-functions, so that the directed complex network model of the product function is obtained.

1.3.3 Modulation of product functions based on genetic algorithm

For the complex network model, the genetic algorithm is used to optimize the network module degree, and the module division scheme of the product system structure and function is obtained.

2. Theoretical Methods

2.1 Functional Base-Related Concepts

Product systems use functional base for functional modeling. Stone [12] and Wood propose the standard of functional base on the functional black box. It is to construct the product function model in the form of moving object. Functional infrastructure model is a tool with multiple tasks, including generation of black box model, generation of function chain and generation of function model by aggregation function chain.

Functional modeling or functional decomposition refers to the decomposition of a complex system or product into smaller, more specific functional units and modules. In order to have a better understand of their components and the interactions between them.

2.2 Relevant Concepts of Complex Networks

(1)Complex network: It is a grid structure composed of node sets V and edge sets E. In terms of G= (V, E). There are four typical types of networks: undirected network, directed network, undirected weighted network and directed weighted network.

(2)Adjacency matrix: The adjacency matrix A of complex networks G=(V, E) can be represented by the square matrix, and the size is $|V|\times|V|$ (V represents the set of nodes, and E represents the set of edges).

(3)Degree: Positive integer can be expressed as the number of edges between k and other nodes. For a complex network with n nodes, the degree of the nodes can be calculated by summing over the adjacency matrix elements.

$$k_i = \sum_{j=1}^{n} A_{ij} \quad (1)$$

In a directed network, the degree of each node can be divided into in degree and out degree. where the in degree of a node indicates the number of edges pointing from another node to that node, while the out degree indicates the number of edges pointing from that node to other nodes. In the undirected network: $k_i = k_i^{in} = k_i^{out}$

(4)Edge betweenness: Represents the number of shortest paths through this edge in the network.

(5)Modularity: It reflects the relative densit y inside the community and the relative sp arsity outside the community, and reveals t he strong and weak characteristics of the c ommunity structure. When the proportion o f edges within the community meets the e xpected value, the module degree is zero, t he maximum upper limit is one. At present, the most commonly used methods of calc ulating modularity are as follows.

$$\lambda_{wd} = \frac{1}{m}\sum_{i,j}\left(w_{ij} - \frac{w_i^{out} w_j^{in}}{m}\right)\delta\left(C_i, C_j\right) \quad (2)$$

Where m is the total number of edges in the network, for the directed network:

$$w = \frac{1}{2}\sum_{i,j} w_{ij} = \frac{1}{2}\sum_i w_i^{out} = \frac{1}{2}\sum_j w_j^{in} \qquad w_j^{in} = \sum_i w_{ij} \quad w_i^{out} = \sum_j w_{ij} \quad (3)$$

C_i, C_j represents the community of i and j. If node i and node j are in the same community, $\delta(C_i, C_j) = 1$. The final λ value range is [0,1].

2.3 GA Concepts

Genetic algorithm is an optimization algorithm [13] that mimics the natural selection and the GA. The starting point of the GA is a population consisting of a certain number of individuals. Once the initial population is generated, the genetic algorithm will evolve at each generation according to the principles of survival of the fittest, generating increasingly excellent and close to the optimal solution of the problem. In each generation, the best performers are selected according to their fitness and recombined by genetic manipulation (crossover and variation) to produce new knotset populations. Figure 1 illustrates the flow of the basic genetic algorithm.

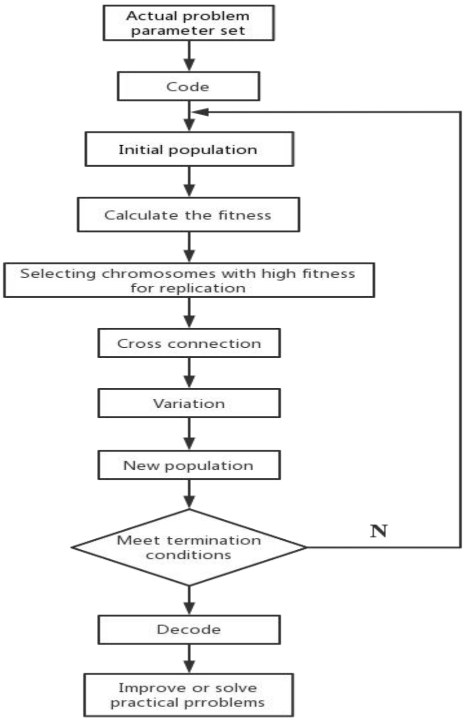

Figure 1. Flow-chart of the Genetic Algorithm

3. Functional Classification and Unified Expression Model of General Aircraft Products

General aircraft product function classification and unified expression is by building low coupling, high cohesion function module to solve the product design in the process of reuse, at the same time in the process of solving product function module can get the product function community, each community on behalf of different function modules, namely the function of general aircraft product classification.

The construction of general aircraft product function classification and unified expression model are mainly divided into three steps: The first step is to build the product function model based on the black box function model; In the second step, based on complex network theory, takes product sub-functions as network nodes, directes edges represent connections between sub-functions, the directed edge weights represent the combined strength between the sub-functions, so as to build the directed complex network model of product function; The third step, based on genetic algorithm, takes the functional module degree of the product as the objective function, uses the connected component of the graph, and the number of variables is the number of network edges, 0 means that this edge is removed, 1 means that this edge is retained. The same connected component represents the same community. Finally, by bringing the objective function into the calculation, the value of the objective and the division of the community are obtained.

3.1 Functional Modeling Based on the Black Box

The process of product function modeling can be briefly summarized in the following three steps:

(1)Establish a black box model: Building a black box model to represent the total function of the product and its input /output function flow. The model describes the overall function of the product and the functional flow relationship between inputs and outputs.

(2)Determine the functional chain: Considering the sub-function that the input stream passes through until it flows out of the black box model or transformed into other function. These sub-functions are recorded in the moving object structure and combined into a functional chain.

(3)Construction of functional structure: All the functional chains obtained in the second step are gathered to form a functional structure model, showing the overall function of the product and the relationship between various functions.

Through the above three steps, a clear product function model can be established to help understand the functional characteristics and behavior of the product, and it is also the basis for building complex product function networks.

3.2 Product Function Oriented Complex Network Modeling

The modeling of the directed complex network of product function is carried out since the black box function modeling. This method takes product sub-functions as network nodes, uses directed edges to represent the connections between sub-functions, uses the weights of edges represent the comprehensive strength of sub-functions, and obtains the directed complex network model of product functions. The specific process can be divided into two steps:

The first step is to build the initial network model. In the initial network model, the node V_i (i=1, 2, 3, ..., n) represents a functional element in the functional model. Thin solid, thick solid, and dashed lines represent the energy flow, matter flow, and information flow. Compared with the functional model, the initial network model is different in expression. The table 1 lists the differences between the initial network model and the functional model.

Table 1. Differences between the Initial Network Models and the Functional Models

	Initial network model	Functional model
Sub-function	V_i	verb-object phrase
Energy flow		XXX
Material flow		XXX
Information flow		XXX

The second step is to build the final network model. According to the mapping relationship between the initial network model and the function model, the initial network model is adjusted and supplemented to obtain the product function oriented complex network model. To obtain the final network model, it is necessary to merge the codirectional edges in the initial network model and define the new weights as follows.

$$E_{ij} = \sum_{k=1}^{3} n_{kij} w_k \quad (4)$$

Where, n_{kij} represents the number of the KTH functional flow, w_k represents the weight of the KTH function flow. In this study, the three functional flows are considered to be equally important in the construction of product functional structure. The specific results are shown in Table 2

Table 2. Functional Flow Weight Table of Complex Network Models

	w_1	w_2	w_3
Functional flow	energy flow	material flow	information flow
Weight	1	1	1

Building a network with nodes, directed edges and wight after considering the different types of function flow weights. In order to describe the complex relationship and overall strength of product function. Finally, obtain the product function adjacency relation table and adjacency matrix.

3.3 Division of Product Functional Modules Based on the Genetic Algorithm

Because of the complexity of complex network, this paper uses the genetic algorithm to obtain the optimal solution to maximize the modular degree of the objective function. Genetic algorithm can perform global search and find the global optimal solution with large search space and uncertain search direction.

Based on the directed complex network community, nodes are divided by community generation, a network is divided by the connected component of the graph and the value of the objective function is calculated by introducing the objective function. The number of variables is the number of network edges and the same connected component represents the same community. This paper takes the maximization of product function modularity as the objective function and uses genetic algorithm to solve it. The specific solving process is shown as follows.

(1)Find the connection matrix of product function.

(2)The objective function is obtained from formula two.

(3)Set the initial population.

(4)Set the probability of crossover and mutation.

(5)Set the variable to the edge of the network.

(6)Maximum interation number of the termination condition.

(7)To obtain the module degree of the optimal product function and the result of the community division.

4. Example Validation (Take the Helicopter as an Example)

4.1 Introduction

In this paper, the power working device of helicopter is taken as a case of modular functional structure. The power system includes the engine and the systems and devices that enable the engine to be installed, used and operated reliably on the helicopter [14]. The structure of helicopter is huge and the modeling process is complex, so it is necessary to reduce the coupling between the functions of the power system mechanism and optimize the module division.

4.2 Establish the Functional Model of the General Aircraft Helicopter Engine System

The Lycoming O-320 is a common piston engine for light aircraft and its working principle are shown below.

(1)A lot of air draws into the front of the engine before taking off, and the air enters the engine through the filter.

(2)Inside the engine, the fuel is injected into the combustion chamber. The combustion chamber is a confined space. The piston is in a downward position before the fuel is injected.

(3)When the fuel enters the combustion chamber, the spark plug will spark and ignite the air and fuel mixture. This causes an explosion, producing high temperature and high-pressure gas that pushing the piston upward.

(4)When the piston rises, it pushes the rod and crankshaft forward. Crankshaft can convert the linear motion of the piston into rotational motion.

(5)The exhaust door will open to expel the burned exhaust gas when the piston reaches the highest point.

(6)As the crankshaft rotates, the piston will drop again, the exhaust door closes, the fuel is injected into the combustion chamber to ignite the mixture and pushing the piston up. This process is repeated until the plane lands.

Functional modeling of the helicopter engine powertrain through the black box model, as shown in Figure 2.

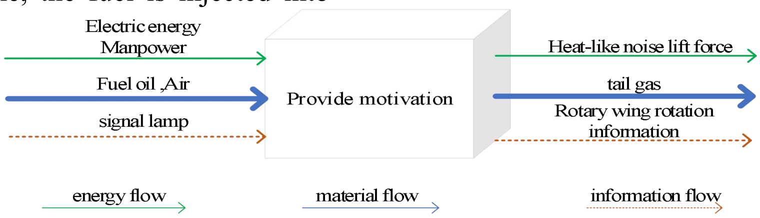

Figure 2. Black Box Diagram of the Product Function

Thinking about some sub-functions that they pass through the black box model from the perspective of the flow of input functions and form a complete functional chain recorded in the format of verb-object phrase.

From the human function model. During the flight, the pilot needs to adjust the throttle as needed to control the speed and altitude of the aircraft. When adjusting the throttle, the pilot needs to be aware of the engine operation and makes sure they are within normal range. The human functional chain model diagram is shown in Figure 3.

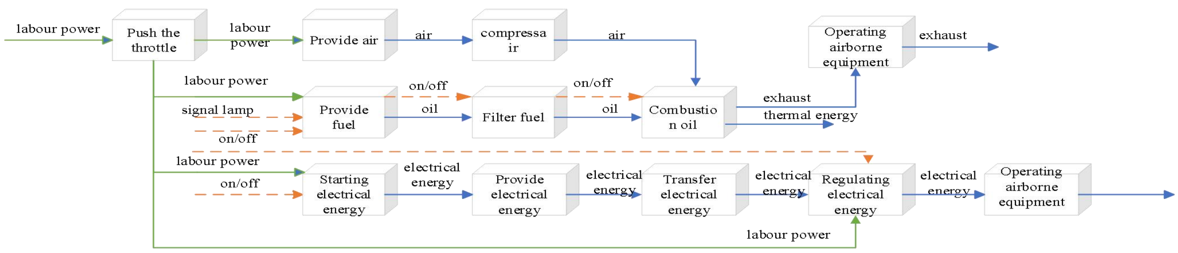

Figure 3. Model Diagram of the Human Functional Chain

The oil system of the engine consists of fuel tank, oil pump, filter and oil cooler, etc. Before starting the engine, the pump pulls oil from the tank and sends it to the lubrication system. In the lubrication system, the oil will lubricate and cool the individual parts of the engine to reduce friction and wear between the parts and to maintain a proper operating temperature. During the operation of the engine, the oil is continuously circulated to keep the engine lubricated and cooled. The oil pump draws the oil from the lubrication system and returns it to the tank. Through this process, the fuel function model is established and shown in Figure 4.

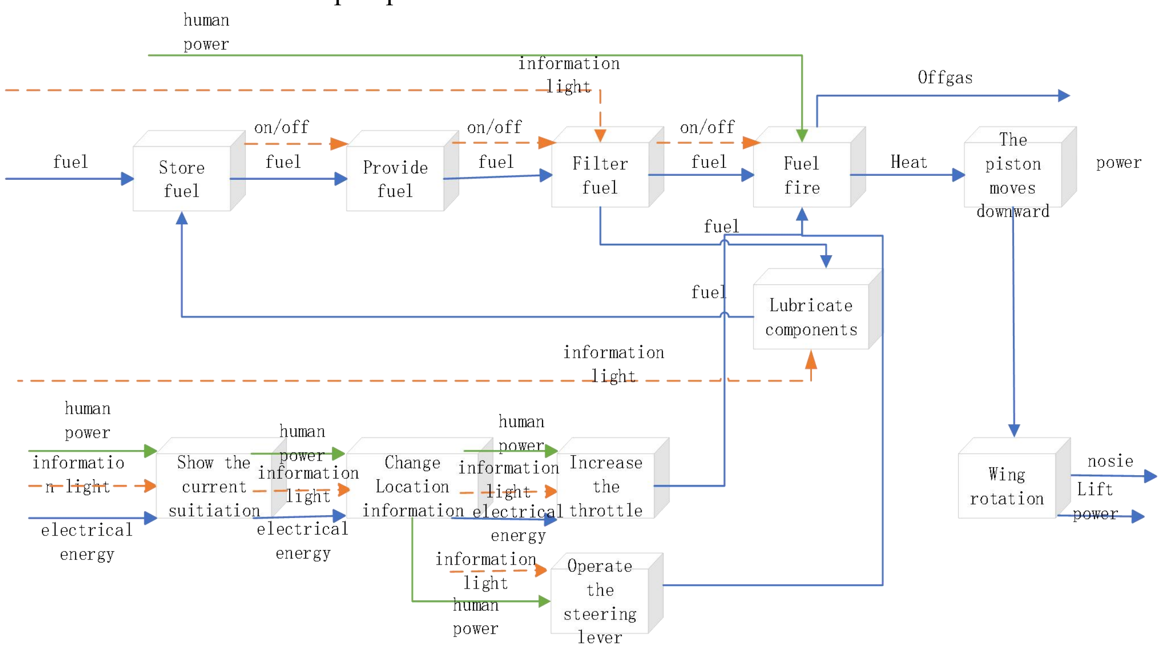

Figure 4. Oil Functional Chain Model Diagram

When starting, electricity is supplied from the aircraft's battery, transferring the rotating power to the engine's crankshaft. Once the engine starts and operates, electricity is generated by the generator and supplied to the entire aircraft electrical system. Electricity is stored in the aircraft's batteries to supply key electrical equipment such as starters and dashboard. The supply and distribution of electric energy is controlled by the aircraft's electrical system. During the flight, the generator constantly charges the battery to keep the battery in reserve for a rainy day. The electric energy function model diagram is shown in Figure 5.

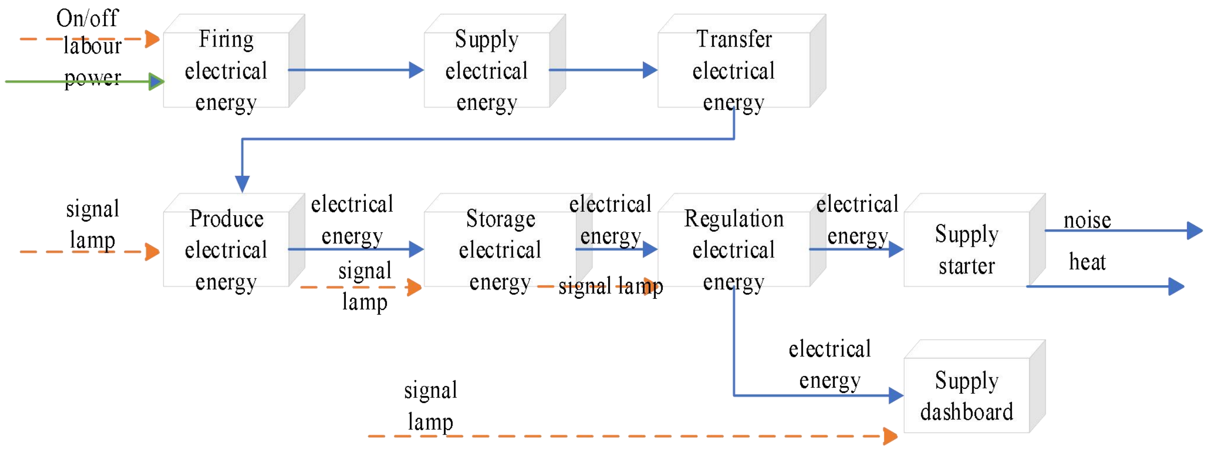

Figure 5. Energy Function Model Diagram

The combination of these functional chains constitutes a functional model of the general aircraft helicopter engine power plant. As shown in Figure 6.

4.3 Weight Complex Network Modeling of

General Aircraft Helicopter Power Plant

Based on the helicopter engine function model, the function network model of the helicopter engine is established by using the network node to represent the sub-functions, using the directed edge to connect the connections between the sub-functions, and using the directed edge weight to represent the strength of the sub-functions. As shown in Figure 7.

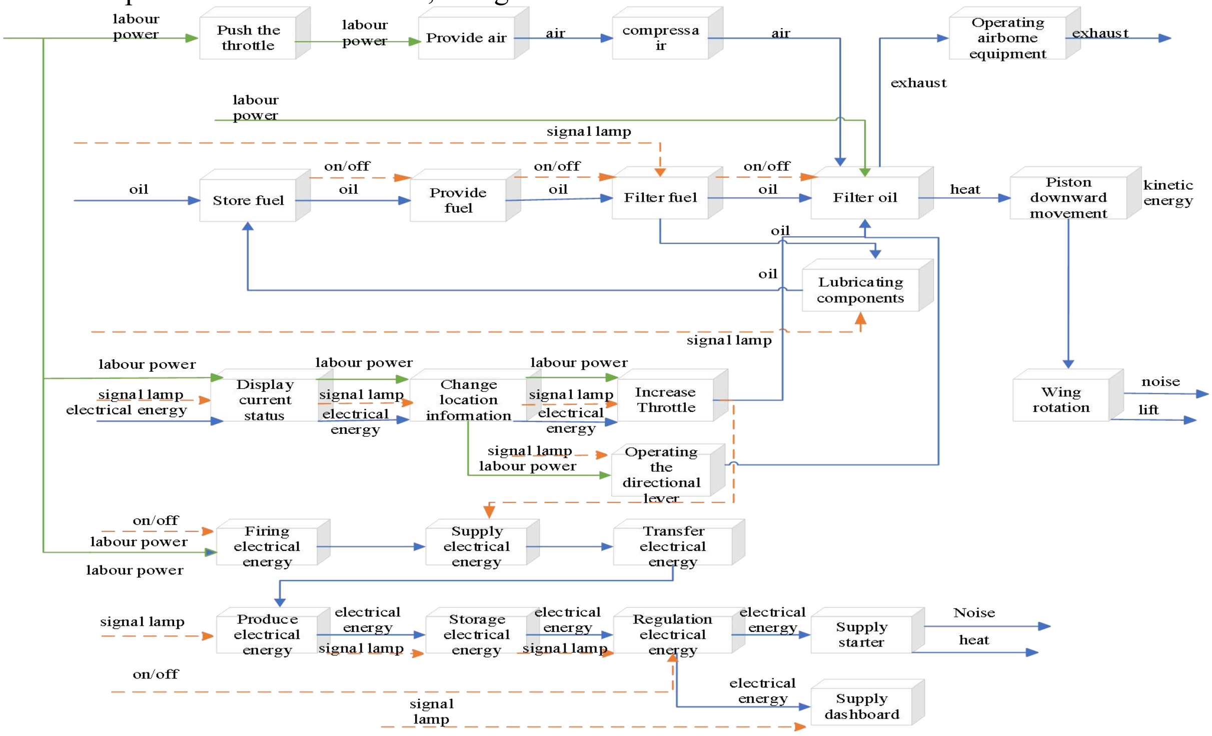

Figure 6. Model Diagram of Product Functional Structure Based on Functional Bases

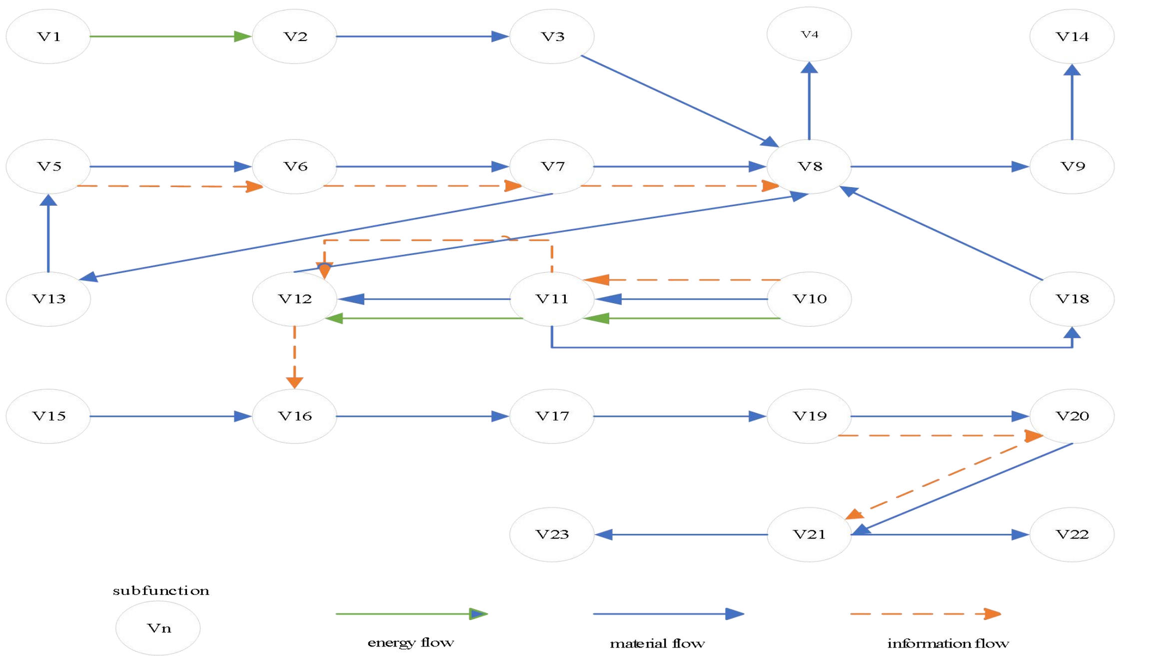

Figure 7. Complex Network Model Diagram of the Product Function

Numbers of nodes represent the corresponding sub-functions, and to clearly understand the specific functions represented by each number, the controls of node digital functions are shown in Table 3.

Table 3. Control Table of Node Functions

Node	Sub-function	Member	Node	Sub-function	Member
1	Push the throttle	Throttle leverair filter	13	Lubricating components	Oil pump
2	Supply air	Air cleaner	14	Wing rotation	Hydraulic system
3	Transfer air	Air inlet duct	15	Starting energy	Power management system
4	Operating airborne equipment	Electrical system	16	Supply of electrical energy	Battery
5	Storage of oil	Fuel pump	17	Transmit electrical energy	Electrical system
6	Fuel supply	Fuel pump	18	Production of electric energy	Generator
7	Filtered fuel	Fuel filter	19	Drive the Helicopter to Rotate	Main rotor, auxiliary rotor
8	Fuel combustion	Cylinder	20	Stored electrical energy	Aircraft battery
9	Piston downward movement	Crankshaft connecting rod	21	Regulated electric energy	Regulator
10	Show current status	Engine control unit	22	Supply starter	Starter
11	Change location information	Navigation system and tachometer	23	Supply instrument Cluster	Instrument board
12	Increase throttle	Throttle handle			

After the initial model of the helicopter engine product function is obtained, the directed edge weight represents the comprehensive strength between the sub-functions, and the directed complex network model of the product function is obtained, as shown in Figure 8.

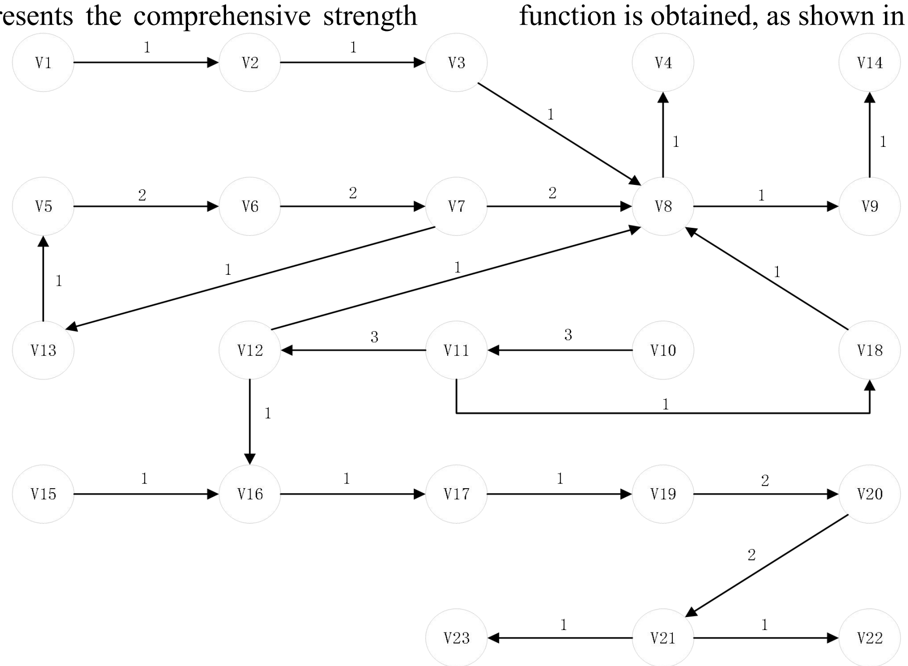

Figure 8. Complex Network Model Diagram of Engine Product Function

Through the functional network model diagram of the general aircraft engine power plant, a functional network model matrix of the general aircraft engine product can be constructed, as shown in equation (5)

$$A_{ij}=\begin{bmatrix} 0&1&0&0&0&0&0&0&0&0&0&0&0&0&\cdots\\ 0&0&1&0&0&0&0&0&0&0&0&0&0&0&\cdots\\ 0&0&0&0&0&0&0&1&0&0&0&0&0&0&\cdots\\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0&\cdots\\ 0&0&0&0&0&2&0&0&0&0&0&0&0&0&\cdots\\ 0&0&0&0&0&0&2&0&0&0&0&0&0&0&\cdots\\ 0&0&0&0&0&0&0&2&0&0&0&0&0&0&\cdots\\ 0&0&0&1&0&0&0&0&1&0&0&0&0&0&\cdots\\ 0&0&0&0&0&0&0&0&0&0&0&0&0&1&\cdots\\ 0&0&0&0&0&0&0&0&0&0&3&0&0&0&\cdots\\ 0&0&0&0&0&0&0&0&0&0&0&3&0&0&\cdots\\ 0&0&0&0&0&0&0&1&0&0&0&0&0&0&\cdots\\ 0&0&0&0&1&0&0&0&0&0&0&0&0&0&\cdots\\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0&\cdots\\ \vdots&\vdots&\vdots&\vdots&\vdots&\vdots&\vdots&\vdots&\vdots&\vdots&\vdots&\vdots&\vdots&\vdots&\ddots \end{bmatrix} \quad (5)$$

4.4 Division of Functional Network Structure Modules of Helicopter Engine Products Based on Genetic Algorithm

The genetic algorithm coding is carried out by MATLAB according to the method of dividing modules by genetic algorithm. The algorithm parameters are set as follows. The objective function is to optimize the maximum modularity of product function. Entering the functional network collar matrix model into an EXCEL document and running the program to get the final plan of module division. The functional network is divided into three communities, and the maximum module value is about 0.55. As shown in Figure 9.

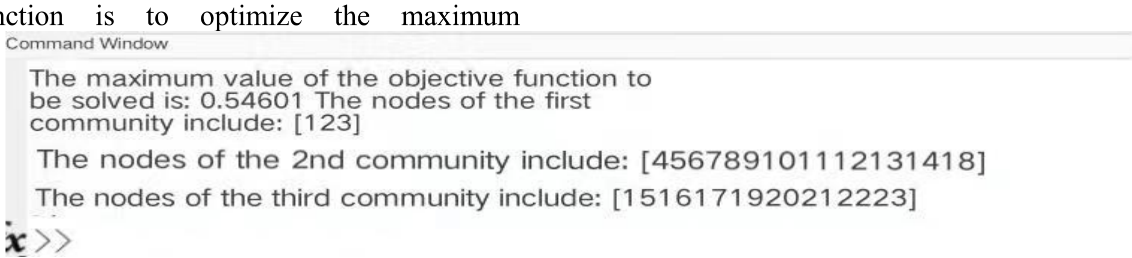

Figure 9. MATLAB Command Run Diagram

In order to visualize the community pattern, the network module division scheme is given as shown in Figure 10.

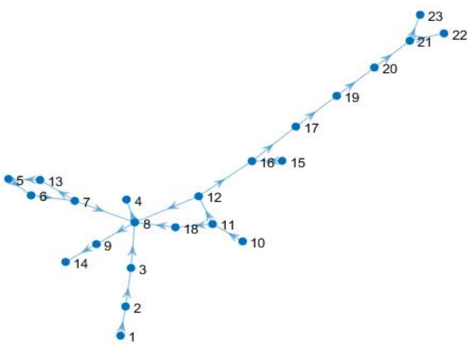

Figure 10. Module Partition Diagram of Functional Network Model

Three communities represent different product function modules. The product function node contained in community one represents the power plant intake function module; Community two represents the power generation module of the power plant; Community three represents the power generation module of the power plant.

4.5 Scheme Result Analysis

To obtain an optimal solution for the modularity of the product functional network, the parameters of the GA were set to an initial population of 100, iterations of 200, with a crossover rate of 0.9 and a variation rate of 0.1. For the complex network of 23 nodes in the text, the maximum network module degree 0.54605 was obtained after 25 iterations, indicating that the optimal solution of this parameter can be fully obtained, as shown in Figure 11.

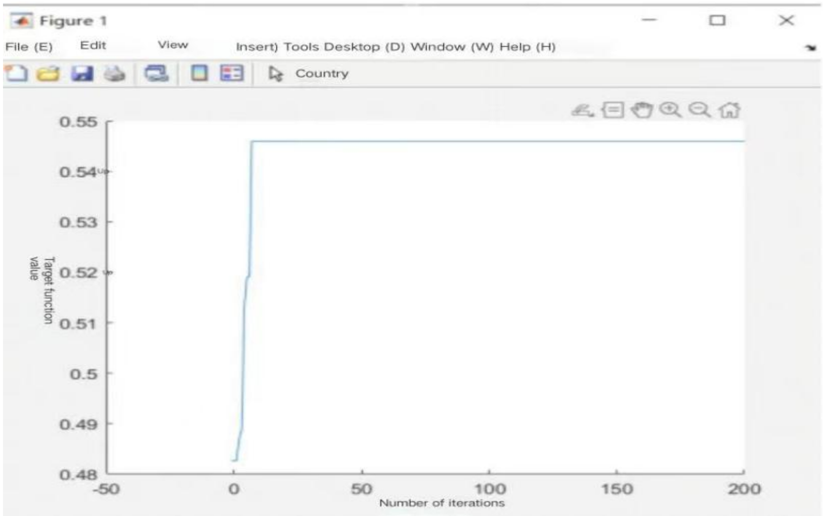

Figure 11. An Iterative Process Diagram of the Modular Degree Optimization of the Objective Function

5. Conclusion

This paper analyzes the present situation of complex product design at home and abroad. Aiming at the problems of product function coupling, iteration and reuse, the product function model is constructed by black-box function model. Through complex network theory, the directed complex network model of product function is constructed. By using genetic algorithm, the objective function value is calculated and the community is divided. Based on this, the classification of product functions and the model of unified expression are proposed. Finally, taking the general aircraft helicopter engine power plant as an example to illustrate the effectiveness of this study. By constructing the black box model of helicopter engine function, the product function structure model diagram and directed network model diagram are established. By using the genetic algorithm, the functional module degree of the engine product is calculated as 0.55. And divided the product function into three communities, which proves the validity and feasibility of this study and provides an effective reference for the design of the product function of general aircraft.

Innovation points and shortcomings

The reuse degree of complex products is mainly reflected in the mapping of product functional structure. The product functional model is constructed through the black box model, the directed complex network model of product function is constructed based on the complex network theory, and the maximum modular degree of the objective function is solved based on the genetic algorithm, and the product function is divided into modules. This method takes into account the directionality of functional nodes and the strength of node connections, which is in line with engineering practice.

In the process of modeling the functional network structure of the product, it is very important to solve the module degree and divide the community. During the iteration process, there may be difficulties in making design decisions, as well as limitations in design time and resources. How to make decisions and adjustments efficiently in the iterative process to achieve optimal design results is a challenging problem. In addition, the specific impact of functional reuse in the design process and the actual operating costs have not been thoroughly studied.

In addition, although the modularity and community division provide an important basis for the unified expression of product functions, the design time and actual running costs in the design coupling, iteration and reuse process of product functions are still needed.

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