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An Evaluation Method for the Skeleton Model Based on Function–Behavior–Structure Correlation Analysis

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Abstract: The skeleton model is an essential tool to support the top-down design of complex products, and the rationality of its design has a significant influence on the detailed design of products. However, the current skeleton models of complex products are mainly designed based on experience, and there is no practical method to judge the rationality of the skeleton model design. This study conducts a component correlation analysis of the skeleton model of complex products. It proposes a method for clustering analysis and evaluating multi-level skeleton models based on the transitive closure method. The effectiveness of the method is verified through a case study of a rocket nose cone's skeleton model. This method provides a scientific analysis method for designers to establish a reasonable skeleton model. In addition, the knowledge description of the skeleton model established in this study lacks sufficient flexibility, and the time complexity of cluster analysis needs to be reduced.

Keywords: skeleton model; knowledge modeling; hierarchical fuzzy clustering; correlation analysis

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1. Introduction

Complex products are quintessential examples of high-end design, and the level of design in complex products symbolizes a country's comprehensive national strength and technological prowess [1]. Large vessels, launch vehicles, armed helicopters, and high-speed trains are typical examples of complex products. The research and development costs of these products are high, and they exhibit characteristics of being knowledge-intensive, customizable in single or small batches, and hold significant importance in maintaining national security and enhancing the standard of living for humanity.

However, the design cycle of complex products is lengthy. A significant challenge in complex product development is ensuring product quality while rapidly realizing and refining product designs [2]. Complex products typically involve knowledge and technology from multiple domains, with many components and complex assembly relationships. This encompasses various structures, mechanisms, and other intricate components and subsystems, often resulting in a multi-layered hierarchical structure. Additionally, subsystems that fulfill the same functionalities are usually spatially separated, leading to complex boundaries and interface parameters within and between different subsystems in structure design, which are difficult to define precisely in the early stages of design. Given the characteristics of complex products, such as their multi-layered hierarchical structures and complex interface parameters, contemporary design firms must rely on skeleton models to complete the design of such products [3,4].

The skeleton model [5] describes a product's spatial position, outline dimensions, and constraint information, serving as a crucial tool for implementing top-down design in complex products. A mouse containing dozens of components allows designers to consider the position and shape of each part through mental simulation. A robotic arm with hundreds of components would likely encounter extensive interference if designed and assembled separately. Agricultural machinery, such as single-bucket excavators and air seeders, comprises thousands to tens of thousands of parts; rocket structural systems contain hundreds of thousands of parts, and a passenger aircraft can have up to millions of parts. The development of such complex products is a systemic engineering challenge. Without the aid of the skeleton model to control key design parameters, issues with the initial design may only be identified during detailed design, requiring designers to spend considerable time modifying the product's three-dimensional model [6]. Therefore, the design of complex products such as launch vehicles and armed helicopters currently relies on the skeleton model to centralize the definition of key design parameters and constraints for the entire product and to transmit overall design information to subsystems or components in a top-down manner, achieving coordination between the overall design and its subsystems.

The skeleton model emerged in response to the increasing complexity of product design and has been applied to the design of various complex products over the past decades. Originating in the 1990s, the importance of the skeleton model has become increasingly significant with the rise in product design complexity. As early as 1993, Kikkawa et al. [7] proposed a method based on constraint graphs to express the interrelation between mechanism modules and designed a constraint-solving algorithm, enabling designers to establish partially undefined mechanism sketches, providing technical support for the top-down design of CAD systems at that time, which essentially utilized the skeleton model in product design. Well-known companies such as Parametric Technology Corporation (PTC, in Boston, MA, USA) and International Business Machines Corporation (IBM, in Armonk, NY, USA) believed that the increasing number of parts and complex features were becoming bottlenecks in the design capabilities of CAD software (such as Catia version 4, Unigraphics version 11, etc.), necessitating the use of contextual design to strengthen the management of component interrelations [8]. In 1999, PTC released Pro/ENGINEER 2000i, which implemented top-down design functionality based on the skeleton model. In a research report [9] by Sandia National Laboratories (Albuquerque, NM, USA), Calton stated that the assembly design of military products requires a series of auxiliary methods such as memory optimization, model simplification, and interrelation management, with the design concept of interrelation management being similar to the skeleton modeling function of Pro/ENGINEER 2000i. The laboratory's software, "Archimedes 3.0", was successfully applied to the product design of Cummins Engine Company (Columbus, IN, USA), Raytheon Missile Systems (Waltham, MA, USA), and Sikorsky Aircraft Company (Stafford, CT, USA). David J. Kasik et al. [10] of Boeing Commercial Airplanes (Seattle, WA, USA) summarized the top ten challenges in CAD, categorizing them into three main types: geometric computation, interaction technology, and product scale. Among them, product scale refers to the issues of representation, sharing, and reuse of design data caused by the increasing complexity of products. For the design of the Boeing 787 passenger jet, different designers pre-assembled various parts of the aircraft and then assembled the product components into the overall skeleton model. Junqiang Wang et al. [11] used the skeleton model to express the overall structure and connection relationships between function units of a precision horizontal machining center, adding non-geometric constraints such as parameters, equations, and rules to the skeleton model. By combining product configuration design knowledge with topological architecture types through the complete

machine tool skeleton model, they improved the level of intelligence in machine tool design. Zhang Zhou et al. [12] achieved rapid design of the overall structure of ships through the skeleton model, associating the hull grillage with the skeleton model to rapidly adjust the hull structure.

The skeleton model plays a crucial role in the design of complex products. However, in the actual product development process, due to the absence of evaluation methods, the rationality of the established skeleton model is difficult to guarantee, posing significant risks to the subsequent detailed design process. For instance, for a product with a simple structure, such as a mouse, a single-layer skeleton model is sufficient to describe the design requirements of all components. However, for products such as launch vehicles or armed helicopters, where the interconnections between various subsystems are complex, a multi-layer skeleton model is necessary to articulate the overall product's design requirements for its subsystems. When designing complex products with multi-layer skeleton models, there is a tendency for confusion in defining the relationships between subsystems, leading to an ill-designed skeleton model. Therefore, this paper proposes a skeleton model evaluation method based on analyzing function–behavior–structure correlations. It combines multi-dimensional knowledge representation to provide a basis for the study of component correlations in the skeleton model and introduces mathematical indicators for the quantitative evaluation of the skeleton model. These can determine whether the skeleton model established by designers is reasonable, supporting the design of complex products. However, the knowledge representation for component correlation analysis still lacks sufficient flexibility. In addition, the time complexity becomes increasingly challenging to handle as the number of components for the skeleton model increases.

The main contributions of this paper include the following:

1. An original method is proposed for the evaluation of complex product skeleton models. Traditional skeleton model design is based on experience, and the absence of quantitative evaluation methods makes it difficult for designers to ensure the rationality of the skeleton model. This study clarifies the basis and quantitative indicators for correlation analysis and demonstrates the method's effectiveness in designing skeleton models for aerospace products.
2. Furthermore, the evaluation method of the skeleton model can be extended to a broader range of complex products (as described in the Appendix A), assisting designers in establishing more rational skeleton models and mitigating the inefficiencies and rework resulting from poorly designed skeleton models.

2. Related Work

2.1. Establishment of the Skeleton Model

The skeleton model has applications in designing complex products such as aircraft, launch vehicles, and ships. However, designers primarily utilize the skeleton model as a design reference, and there is yet to be a systematic approach developed on using the elements within the skeleton model and constructing a skeleton model based on product design requirements.

Junqiang Wang et al. [3] considered the skeleton model to be a three-dimensional layout model expressing the basic CAD structure of a product composed of elements such as reference planes, reference axes, curves, surfaces, coordinate systems, and reference points. The skeleton model was established through the combination of these reference features and parameter-driven rules. Demoly et al. [13] defined the skeleton model for rapid modeling of human hand bones, considering it a carrier integrating knowledge of human anatomy and biomechanics, thus representing a knowledge model. In another study by Demoly et al. [14], the skeleton model was defined as the base for product

component assembly. By assembling numerous components onto a geometric skeleton model, it was possible to specify a better assembly sequence in the early stages of product development and to enable parallel product development by multiple design teams. Chu et al. [15] viewed the skeleton model as an essential tool for conveying design intent, defining product structure, and ensuring the controlled release of design parameters. The skeleton model was primarily used for design parameter transfer in top-down design, yet the intricate mechanism of parameter transmission still requires optimization. Duhwan et al. [16] considered the skeleton model to be a neutral file, including geometric entities: references, curves, and sketches, as well as non-geometric entities: parameters, equations, and rules. Teng Wang [4], a designer in this field, has not provided an academic definition of the skeleton model but outlined the information it contains in the actual design of complex products, namely coordinate systems, axes, contours, and mating surfaces.

While the skeleton model is widely applied in practical complex designs, no comprehensive and accurate definition exists. Researchers primarily utilize the skeleton model to address specific issues within their design domains. Thus, the emphasis on the definition of the skeleton model varies across different studies. However, the following two characteristics of the skeleton model can be summarized:

1. The skeleton model serves as a reference for constraining the product assembly model. It defines the key structural parameters of product design through geometric elements such as reference points, coordinate systems, contours, and geometric constraints. Subsequently, it describes the critical geometric information of complex products through these geometric elements and constraints.
2. The skeleton model is primarily utilized in the innovative design of complex products, such as those in the aerospace and automotive industries that require the design of high-order surfaces. During the development of new products, multiple design teams typically work in parallel, necessitating conceptual design followed by detailed design. The transfer of key design parameters from the conceptual to the detailed design phase relies on the skeleton model.

In computer-aided design, skeleton modeling has become a standard key technology, designers facilitate the design of many modern industrial products with tools that support skeleton modeling. The skeleton model assumes a central role in multi-level product structure design [17], precisely controlling and transmitting positional parameters between design units, ensuring consistency in spatial positioning, interface types, and assembly methods. In innovative design, the skeleton model provided a method for innovative topological design by closely integrating components' material properties and functions, assisting designers in considering the entire lifecycle of products at an early stage [18]. In additive manufacturing, the skeleton model was used to construct precise lattice structures composed of basic elements such as points, lines, and sections [19]. The skeleton model could accurately generate complex three-dimensional lattice structures. The skeleton model also contributed to converting from structural optimization results to parametric CAD modeling, aiding in the automatic transformation of structural optimization results into parametric three-dimensional models used in CAD systems [20], significantly enhancing design efficiency. Congqian Qi et al. [18,21] at Tongji University proposed implementing a top-down product design with a basic top-level skeleton. They utilized the copy reference function of Pro/ENGINEER 2001 to achieve serialized variant designs for mobile phones and audio devices. Additionally, the skeleton model was also used to measure the geometric complexity of three-dimensional models [22] or extract the part skeleton through a deep learning algorithm to describe the pose of the part [23].

In summary, different scholars have varying interpretations and descriptions of the skeleton model, and there is yet to be a systematic and operational method for establishing

the skeleton model. Although some CAD software tools support skeleton modeling, designers must still use their experience to define the skeleton model digitally. Since subsequent detailed design must be conducted within the constraints of the skeleton model, it is imperative to evaluate the skeleton model to ensure the rationality.

2.2. Evaluation of the Skeleton Model

Existing research on the evaluation of skeleton models primarily encompasses two broad categories: one involves objective computational methods, while the other employs subjective evaluation techniques. These will be discussed separately below.

He et al. [24] established a parameterized skeleton model and evaluated it using finite element analysis, which was preliminarily applied in the truss design of tower cranes. The study facilitated the dynamic information association and integration between design models and analysis models based on the parameterized skeleton model. Claudio et al. [25] expressed engineering knowledge of the assembly process through mathematical formulas and associated it with the components of the skeleton model. Kinematic analysis was applied in the early stages of product development to assess the effectiveness and applicability of the skeleton model, which was applied in the design of tube bundle cleaners. Egon et al. [26] utilized the skeleton model in rocket nozzle design; the skeleton models in this research included the following information: engineering requirements, performance requirements, materials, and geometric shapes. Through finite element analysis calculations, the product's geometric shape and topological structure changes were driven by material properties. The aforementioned objective calculation methods primarily aim to design skeleton models for simple structures with less geometric and constraint information. Designers can quickly establish corresponding skeleton models and perform simulation calculations. However, this method does not apply to the evaluation of skeleton models for complex products.

Subjective evaluation methods are primarily oriented toward complex products with a lengthy design cycle and knowledge-intensive characteristics. For instance, in the case of aerospace product skeleton modeling schemes, subjective scoring is conducted using a multi-dimensional scale. By comparing the actual design scheme with the ideal scheme proposed by experts, subjective ratings are obtained by assessing the convenience and efficiency of the skeleton model. This approach yields an evaluation result for the skeleton model, and this evaluation scale method is akin to the TOPSIS evaluation method [27]. The quality function deployment (QFD) method was used in NASA's space center research and development tasks [28]. It involved extracting over 40 capability requirement indicators such as connection and separation capabilities, design modularity, and interface standardization and ranking their importance. Subsequently, the compliance of five space platforms with these indicators was evaluated, enabling a preliminary assessment of the overall aerospace product design scheme. The QFD method is a commonly used approach for evaluating conceptual design schemes in system engineering [29]. Additionally, the skeleton model is primarily defined during the conceptual design phase, making the QFD method highly suitable for the preliminary evaluation of complex system skeleton models. However, these methods heavily rely on expert subjective evaluations, often necessitating the organization of multiple expert teams for review and scoring, which significantly consumes human resources.

In summary, for products with a small number of parts and a simple hierarchical structure, designers can specify the details of the skeleton model based on experience and then determine the reasonableness of the skeleton model design through simulation and other methods. However, the skeleton model has multiple levels and complex functions for products such as launch vehicles and armed helicopters. During the design process, it

is necessary to consider the interrelation between different structures. Designers cannot directly conceive of a specific skeleton model, making it difficult to determine whether the design of the skeleton model is reasonable. Therefore, there is an urgent need to study quantitative evaluation methods for the skeleton model of complex products.

3. Evaluation Method for the Skeleton Model

Based on the actual process of designing a skeleton model in the corporation, this study specified the principle to determine what kind of skeleton model is reasonable. During the design process, the overall designer conducts a hierarchical design of the skeleton model based on different components' functions, disciplines, spatial requirements, etc. Subsequently, the top-level skeleton model is fully defined, and the partially defined lower-level skeleton models are distributed to other design teams for further design refinement. The overall designer categorizes the skeleton models of components with strong function and structure correlations into a single group and distributes them to subsequent detailed designers. Therefore, the principle for evaluating the skeleton model is clarified. The stronger the correlation between components under the same parent node in the skeleton model and the weaker the correlation between components under different parent nodes, the more conducive it is for subsequent detailed design referencing the skeleton model, and the more reasonable the design of the skeleton model is.

Based on the principle of evaluating the skeleton model, this study proposes a method for assessing the skeleton model of complex products, as illustrated in Figure 1. Initially, a knowledge representation model for the skeleton model's function, behavior, and structure is established. Subsequently, the correlation analysis of the function, behavior, and structure of the components within the skeleton model is utilized to express the connections between different components quantitatively. Finally, the transitive closure method is employed for hierarchical fuzzy clustering analysis of the components, and an evaluation of the complex product skeleton model is achieved based on the silhouette coefficient.

3.1. Creation of Knowledge Representation Models for the Skeleton Model

Given that the skeleton model is primarily utilized for the innovative design of complex products, it adopts a top-down design approach: requirement analysis, function decomposition, analysis and calculation of kinematic relationships and actuators, structure scheme design, and scheme refinement. Consequently, the design process outlined above is summarized as function decomposition, behavior design, and structure design. The evaluation of the skeleton model also involves analyzing function, behavior, and structure connections. Knowledge representation models are established based on the Backus normal form (BNF) [30].

3.1.1. Function Description Knowledge Model

This study established a function description knowledge model for the skeleton model, aimed at describing the functionality of each component. Function refers to the description of the role a component in the skeleton model can perform, which typically evolves from design requirements. A skeleton model corresponds to one or more associated components collaborating to achieve a specific function. For instance, the helicopter landing gear's skeleton model comprises connecting rods, buffer sleeves, wheels, etc. These components collectively fulfill the buffering function during a helicopter landing.

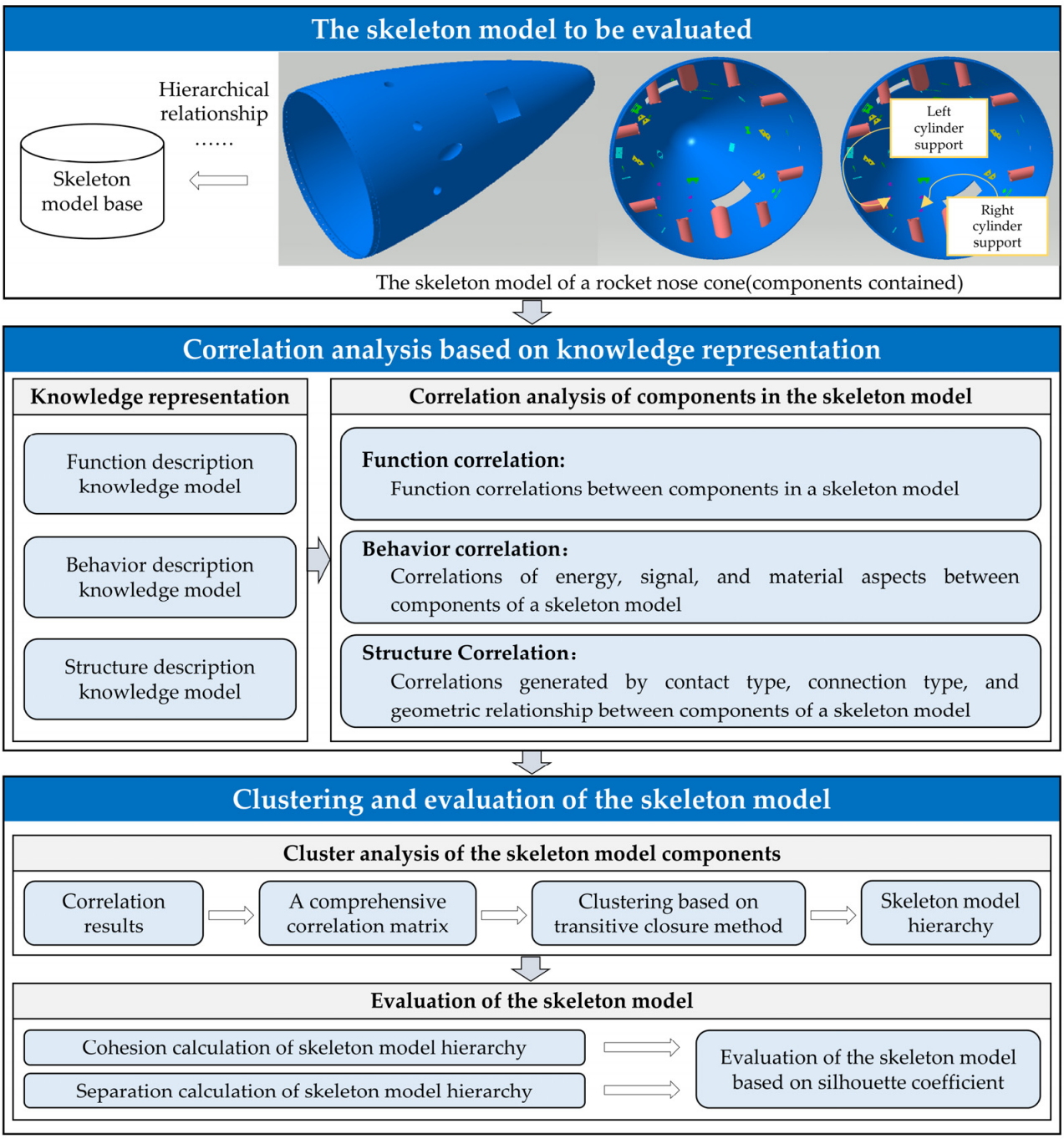


Figure 1. The framework of the method for evaluating skeleton models based on correlation analysis.

Functional-oriented design typically occurs during the conceptual design of a product, primarily involving the transformation of fragmented design requirements into structured or semi-structured functional descriptions. The initial function design of a complex product is abstract, and as design requirements and application scenarios become increasingly clear, the description of product functions becomes more specific. Typically, the refinement of function descriptions is achieved through functional decomposition, meaning that functions can be broken down into multiple layers of sub-functions.

Design for complex products such as helicopters and launch vehicles primarily adopts a functional organization. For instance, rocket design involves specialized structure, electrical, attitude control, aerodynamics analyses, etc. The various functions of the rocket are designed and implemented by distinct working groups; hence, the function model also incorporates the discipline to which it belongs. This study integrates the conceptual design

methodology of Stone et al. [31], defining the functions of components in the skeleton model into three levels and eight major categories, and on this basis, establishes a function description knowledge model oriented towards the skeleton model, as illustrated in Figure 2. In this knowledge model, the larger the numerical "Function Level" is, the more specific the function of the described component becomes.

<Function Knowledge> ::= <Skeleton Model Component> <"Have_Function"> <Function>
<Skeleton Model Component> ::= <Component Name> <Component Type> <Basic information description of the component>
<Component Name> ::= <The full name or abbreviation of any skeleton model>
<Component Type> ::= "Top Skeleton Model" | "Middle Layer Skeleton Model" | "Bottom Skeleton Model"
<Basic information description of the component> ::= <Any basic information describing the component>
<Function> ::= <Function Name> <Function Type> <Basic information description of the funtion> <The discipline to which the function belong>
<Function Name> ::= <The full name or abbreviation of any function>
<Function Type> ::= (<Signal Processing> | <Branch> | <Channel> | <Provision> | <Support> | <Connect> | <Control Magnitude> | <Convert>) <Function Level>
<Function Level> ::= 1|2|3
<Basic information description of the function> ::= <Any basic information describing the function>
<The discipline to which the function belongs> ::= <Mechanism> | <Chemistry> | <Optics> | <Dynamics> | <Acoustics> | <Electromagnetics > | <Thermodynamics> | <Biomechanics> | <Other disciplines>

Figure 2. Function description knowledge model.

3.1.2. Behavior Description Knowledge Model

This study established a behavior description knowledge model for the skeleton model. Behavior refers to the connections among components within the skeleton model regarding energy, signal, and material, which arise in various scenarios during the product design, production, and even operational phases. The product is essentially the outcome of the skeleton model's detailed design, prototype trial, and finished product production. Therefore, in the design and evaluation of the skeleton model, it is also necessary to consider the behavior relationships among different components in various scenarios related to the product to ensure that the product can fulfill the required functions according to the expected behaviors. Regarding the energy connection, take the scenario of a helicopter cruising flight. During the design of the helicopter's skeleton model, it is necessary to specify how many transmission shafts, reducers, and engines are included in the transmission system and to calculate the rotational speeds of the rotor and tail rotor. Energy connections exist among the transmission shafts, reducers, engines, and tail rotors. Regarding the signal connections, when a rocket adjusts its attitude, it receives material support from fuel and control signals provided by the navigation device, which constitutes the signal connection. Regarding the material connection, before a launch vehicle delivers the payload to the predetermined orbit, the storage tank provides fuel to the propulsion and attitude control systems.

To illustrate the behavior relationships, consider the following example. Upon separation from the propulsion module, the nose cone initially deploys the metal shell, thereby exposing the satellite to the space environment. Subsequently, the satellite's orientation is adjusted using attitude control rockets. The behavior relationships among the primary components in this scenario are illustrated in Figure 3.

Figure 3 essentially represents the behavior relationships among different components, as analyzed based on the operational scenarios of the product. During the overall design phase of the product, designers analyze the component relationships under multiple operational scenarios, thereby establishing connections among different components in terms of energy, signal, and material. This article abstracts a behavior knowledge representation model to express behavior knowledge in a unified form, as illustrated in Figure 4. The case study section of this article will construct knowledge representation instances based on this model.

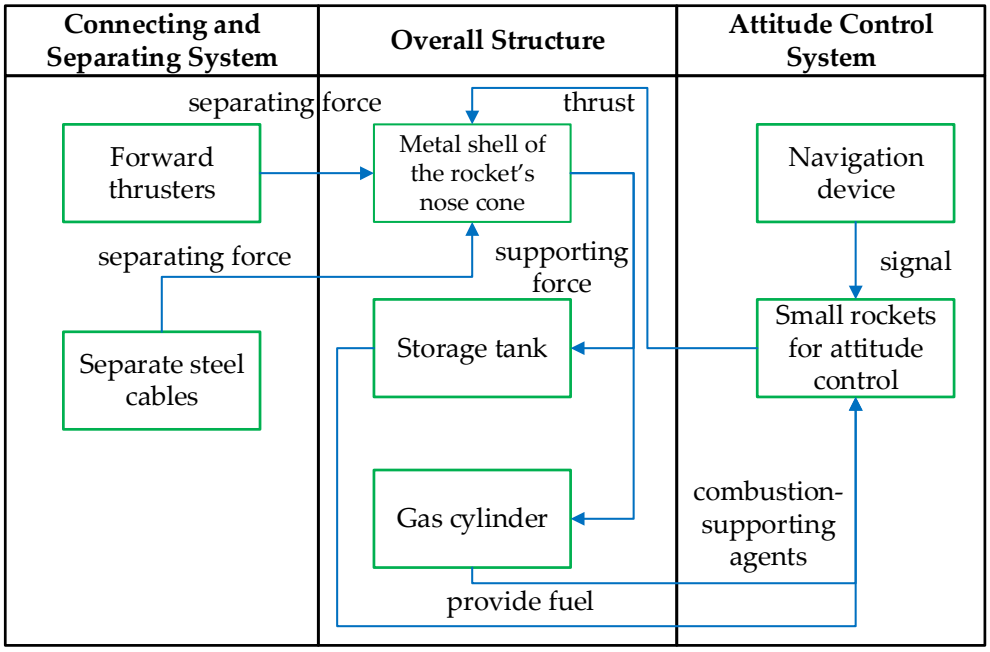


Figure 3. Behavior relationship of certain components in a rocket.

<Behavior Knowledge> ::= <Skeleton Model Component> <Behavior> <Skeleton Model Component>
<Skeleton Model Component> ::= <Component Name> <Component Type> <Basic information description of the component>
<Component Name> ::= <The full name or abbreviation of any skeleton model>
<Component Type> ::= "Top Skeleton Model" | "Middle Layer Skeleton Model" | "Bottom Skeleton Model"
<Basic information description of the component> ::= <Any basic information describing the component>
<Behavior> ::= <Behavior Name> <Behavior Type> <Basic information description of the behavior>
<Behavior Name> ::= <The full name or abbreviation of any behavior>
<Behavior Type> ::= (<Energy Connection> | <Signal Connection> | <Material Connection>) <Behavior Correlation>
<Behavior Correlation> ::= 0.8|0.6|0.2|0
<Basic information description of the behavior> ::= <Any basic information describing the behavior>

Figure 4. Behavior description knowledge model.

3.1.3. Structure Description Knowledge Model

This study established a structure description knowledge model for the skeleton model. The structure knowledge is abstracted as the relationships between components of the skeleton model. Since multiple relationships may exist simultaneously between two components of the skeleton model, the relationships between components can be divided into basic component relationships and combined component relationships. Synthesizing the research of Ma Songhua and Chen Jing [32,33], a structure description knowledge model of the skeleton model is established. In the knowledge model proposed in this study, the basic structure relationships among components include hierarchical relationship, assembly relationship, and association relationship, as illustrated in Figure 5. Hierarchical relationship is used to describe multi-level product structures, while assembly relationship denotes the contact, joint, and geometric relationship among different components. Association relationship refers to structure relationship beyond the aforementioned hierarchical and assembly relationships.

3.2. Correlation Analysis of Components in the Skeleton Model

The analysis of the interrelation of skeleton model components encompasses three aspects: function, behavior, and structure, with the self-related value for each element set to 1. The following provides a detailed analysis of the correlations in these three aspects.

<Structure Knowledge> ::= <Skeleton Model Component> (<Basic Component Relationship> | <Combined Component Relationship>) <Skeleton Model Component>
<Skeleton Model Component> ::= <Component Name> <Component Type> <Basic information description of the component>
<Component Name> ::= <The full name or abbreviation of any skeleton model>
<Component Type> ::= "Top Skeleton Model" | "Middle Layer Skeleton Model" | "Bottom Skeleton Model"
<Basic information description of the component> ::= <Any basic information describing the component>
<Combined Component Relationship> ::= <Basic Component Relationship> {<Basic Component Relationship> | <Combined Component Relationship>}
<Basic Component Relationship> ::= <Hierarchical Relationship> | <Assembly Relationship> | <Association Relationship>
<Hierarchical Relationship> ::= <Composition Relationship> | <Inheritance Relationship>
<Composition Relationship> ::= "Belongto_singleMachine" | "Belongto_subsystem" | "Belongto_product" | <Other composition relationships>
<Inheritance Relationship> ::= "Is_typeOf" | "Is_instanceOf" | <Other inheritance relationships>
<Assembly Relationship> ::= <Contact Type> | <Joint Type> | <Geometric Relationship>
<**Contact Type**> ::= (<Multifaceted Contact> | <Multiline Contact> | <Multipoint Contact> | <One Side Contact> | <Unilineal Contact> | <Single Point Contact> | <No Contact>) <Contact Correlation>
<Contact Correlation> ::= 1.0|0.9|0.8|0.6|0.4|0.2|0

<**Joint Type**> ::= (<Permanent Joint> | <Strong Fixed Joint> | <Weak Fixed Joint> | <Detachable Joint> | <Mobile Joint> | <No Joint>) <Joint Correlation>
<Joint Correlation> ::= 1.0|0.8|0.6|0.4|0.2|0
<Permanent Joint> ::= "Welding" | "Bonding" | "Casting"
<Strong Fixed Joint> ::= "Hot-pressing" | "Shrink Fit"
<Weak Fixed Joint> ::= "Key Joint" | "Riveting"
<Detachable Joint> ::= "Screw Joint"
<Mobile Joint> ::= "Translation Pair" | "Spring" | "Pinned Joint" | "Hinge" | "Hook Coupling"
<No Joint> ::= <Any situation where there is no joint between two components>

<**Geometric Relationship**> ::= (<Rigorous Geometric Relationship> | <General Geometric Relationship> | <Strict constraint on installation space> | <General constraint on installation space>) <Geometric Correlation>
<Geometric Correlation> ::= 0.8|0.6|0.4|0.2
<Rigorous Geometric Relationship> ::= "Parallelism" | "Coaxiality" | "Squarenness" | "Symmetry"
<General Geometric Relationship> ::= <Any situation where there is a physical relationship between two components but no specific geometric tolerance requirements >
<Strict constraint on installation space> ::= <Any situation where there are strict installation space constraints between two components >
<General constraint on installation space> ::= <Any situation where there is a weak installation space limit between two components >

<Association Relationship> ::= <Any other relationship between two components other than the assembly and hierarchical relationships >

Figure 5. Structure description knowledge model.

3.2.1. Function Correlation

The concept of function correlation analysis involves the quantitative description of the function connection among different components within the skeleton model. Existing research primarily quantifies function correlation through subjective assignment, which does not align with the habits of designers and involves a significant workload. A complex skeleton model is associated with dozens or even hundreds of components in the design process. If one manually assigns function correlation between these components, it would require thousands or even millions of subjective judgments, severely impacting design efficiency. For the components of the skeleton model, based on the hierarchical levels of functions in their function models and the respective disciplines they belong to, this study defines function correlation, as illustrated in Equation (1):

$$f(a,b) = l_1 t(a,b) + l_2 m(a,b) \tag{1}$$

$f(a,b)$ denotes the function correlation between components a and b, $t(a,b)$ represents the correlation coefficient determined by the hierarchy of functions, and $m(a,b)$ denotes the correlation coefficient determined by the discipline to which the functions belong. l_1 and l_2, respectively, represent the weights of the two types of correlation coefficients, which are empirically assigned values, $l_1 = 0.5$ and $l_2 = 0.5$.

The value of $t(a,b)$ is determined based on the function hierarchy, with the assignment rules outlined in Table 1. The higher the function hierarchy, the more specific the function description becomes. When components a and b do not belong to the same secondary function, assigning the relevance between different functions in conjunction with domain-specific expertise is necessary.

Table 1. Correlation determined by function hierarchy.

Component Function Hierarchy	$t(a,b)$
Components a and b are subordinate to the same tertiary function	1
Components a and b are classified under the same secondary function but not under the same tertiary function	0.8
Components a and b do not belong to the same secondary function	0.6, 0.4, 0.2 or 0

The skeleton model of complex products comprises many components, and the definition of function connections is conducted by the matrix for the rules of function correlation, as illustrated in Figure 6. By solidifying the connections between different functions within the program, automated assignment of function correlations for many components can be achieved.

Function Level	2	Signal Processing				Branch				Channel					Provision		Support			Connect		Control Magnitude			Convert
2	3	indicate	display	sense	measure	separate	remove	refine	dissipate	transport	transmit	import	export	rotate	supply	store	stop	position	stabilize	mix	couple	actuate	change	regulate	convert
Signal Processing	indicate	1	0.8	0.8	0.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	display	0.8	1	0.8	0.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	sense	0.8	0.8	1	0.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	measure	0.8	0.8	0.8	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Branch	separate	0	0	0	0	1	0.8	0.8	0.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	remove	0	0	0	0	0.8	1	0.8	0.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	refine	0	0	0	0	0.8	0.8	1	0.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	dissipate	0	0	0	0	0.8	0.8	0.8	1	0.6	0	0	0	0	0	0	0	0.6	0.6	0	0	0	0	0	0
Channel	transport	0	0	0	0	0	0	0	0.6	1	0.8	0.8	0.8	0.8	0	0	0.4	0.4	0.4	0	0	0.6	0.6	0.6	0
	transmit	0	0	0	0	0	0	0	0	0.8	1	0.8	0.8	0.8	0	0	0.4	0.4	0.4	0	0	0.6	0.6	0.6	0
	import	0	0	0	0	0	0	0	0	0.8	0.8	1	0.8	0.8	0	0	0.4	0.4	0.4	0	0	0.6	0.6	0.6	0
	export	0	0	0	0	0	0	0	0	0.8	0.8	0.8	1	0.8	0	0	0.4	0.4	0.4	0	0	0.6	0.6	0.6	0
	rotate	0	0	0	0	0	0	0	0	0.8	0.8	0.8	0.8	1	0	0	0.4	0.4	0.4	0	0	0.6	0.6	0.6	0
Provision	supply	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.8	0	0	0	0	0	0	0	0	0
	store	0	0	0	0	0	0	0	0	0	0	0	0	0	0.8	1	0	0	0	0	0	0	0	0	0
Support	stop	0	0	0	0	0	0	0	0	0.4	0.4	0.4	0.4	0.4	0	0	1	0.8	0.8	0	0	0.2	0.2	0.2	0
	position	0	0	0	0	0	0	0	0.6	0.4	0.4	0.4	0.4	0.4	0	0	0.8	1	0.8	0	0	0.2	0.2	0.2	0
	stabilize	0	0	0	0	0	0	0	0.6	0.4	0.4	0.4	0.4	0.4	0	0	0.8	0.8	1	0	0	0.2	0.2	0.2	0
Connect	mix	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.8	0	0	0	0
	couple	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.8	1	0	0	0	0
Control Magnitude	actuate	0	0	0	0	0	0	0	0	0.6	0.6	0.6	0.6	0.6	0	0	0.2	0.2	0.2	0	0	1	0.8	0.8	0
	change	0	0	0	0	0	0	0	0	0.6	0.6	0.6	0.6	0.6	0	0	0.2	0.2	0.2	0	0	0.8	1	0.8	0
	regulate	0	0	0	0	0	0	0	0	0.6	0.6	0.6	0.6	0.6	0	0	0.2	0.2	0.2	0	0	0.8	0.8	1	0
Convert	convert	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

Figure 6. Matrix for the rules of function correlation.

In addition, $m(a,b)$ is determined by the disciplines to which the functions belong, initially categorized into fields such as mechanism, dynamics, electromagnetics, and thermodynamics, corresponding to the diverse disciplines involved in designing complex products, such as aerospace.

3.2.2. Behavior Correlation

Behavior correlation analysis necessitates integrating energy, signal, and material connections among components within the skeleton model. As the skeleton model is an information carrier for constraining the assembly model, designers must clarify the interactions between different components during the skeleton modeling phase to achieve specific functions. For instance, in designing the transmission system of a helicopter, it is essential to precisely define the main dimensions and reduction ratios of multi-stage transmission shafts and reducers during the skeleton modeling phase. This process requires determining the energy transfer relationships among components along the transmission path and clarifying how the control signals for variable speed are transmitted to the transmission system. Given the hundreds involved, designers find identifying the behavior correlations among all components challenging. This is precisely the skeleton model's application scenario, utilized to clarify the primary design constraints, allowing designers to ascertain the most significant energy, signal, and material connections. The behavior correlations defined in this study refer to the research conducted by Zhang Zhengxin [34]. The value assignment rules are outlined in Table 2.

Table 2. Behavior correlation value table.

Correlation of Component Behavior	Behavior Correlation Value
An energetic linkage exists between *a* and *b*	0.8
A signal linkage exists between *a* and *b*	0.6
A material linkage exists between *a* and *b*	0.2

3.2.3. Structure Correlation

The structure correlation primarily assesses the contact types, joint types, and geometric relationships among the components of the skeleton model. These three types of structure connections are explained below. The contact types between the components of the skeleton model refer to the contact between points, lines, and surfaces. Skeleton models typically do not possess entity features; in conventional physical assembly models, point contact and line contact types are rarely seen. However, the contact types in skeleton models are primarily point and line contacts. Joint types are akin to features in mechanical assembly, such as riveting, screw joints, and hinges. Although skeleton models lack physical characteristics, the elements such as points, lines, and surfaces correspond to mechanical structures, and joint types describe the assembly features of the skeleton model. Geometric relationships refer to the geometric tolerances or spatial constraints determined during the skeleton modeling phase. Considering that skeleton model does not have entity features, this study proposes the quantitative basis for the structure correlation of the skeleton model, as shown in Table 3.

Table 3. Structure correlation value table.

Relation of Component Structure	Structure Correlation	Description
Contact types	1.0	There exist multifaceted contacts between *a* and *b*
	0.9	There exists multi-line contact between *a* and *b*
	0.4	There exists unilineal contact between *a* and *b*
Joint types	0.8	Components *a* and *b* are fixedly connected, making them difficult to disassemble
	0.4	Components *a* and *b* are fixedly connected and can be disconnected
	0.2	Component *a* is in mobile connectivity with component *b*
Geometric relationships	0.8	Components *a* and *b* possess a rigorous geometric relationship
	0.4	Components *a* and *b* are subject to strict constraints on installation space

Given that products in aerospace and other industries often need to consider the distribution of the center of mass or dynamic balance requirements, the spatial distribution and symmetry of some important components must be considered during the skeleton modeling phase, such as the main structure members, load-bearing parts, and power units. In contrast, seals and fasteners do not need to be considered.

The skeleton model seldom involves product dimensional details, and much of the design information is not defined, making it challenging for designers to comprehensively consider all components with contact, joint, and geometric relationships. Furthermore, components of the skeleton model may not necessarily possess all three types of relationships simultaneously. To ensure that important structure connection information is not lost during the calculation process, structure correlation is computed using Equation (2):

$$s(a,b) = \max\{s_1(a,b), s_2(a,b), s_3(a,b)\} \quad (2)$$

$s_1(a,b)$ denotes the contact correlation of the components a and b, $s_2(a,b)$ represents the joint correlation, and $s_3(a,b)$ signifies the geometric correlation, with default values of 0 for $s_1(a,b)$, $s_2(a,b)$, and $s_3(a,b)$. $s(a,b)$ denotes the structure correlation of the components.

3.2.4. Comprehensive Correlation

A comprehensive correlation can be derived by integrating the weighted correlations of components within the skeleton model in terms of function, behavior, and structure. The calculation method is shown in Equation (3):

$$z(a,b) = \omega_f f(a,b) + \omega_{be} be(a,b) + \omega_s s(a,b) \tag{3}$$

where ω_f, ω_{be}, and ω_s represent the weight coefficients of the components' function, behavior, and structure correlations, with the sum of the weight coefficients being 1. The weight coefficients can be obtained through the analytic hierarchy process or expert experience analysis. In this study, ω_f, ω_{be}, and ω_s are set at 0.6, 0.1, and 0.3. $f(a,b)$, $be(a,b)$ and $s(a,b)$ denote the components' function, behavior, and structure correlations, while $z(a,b)$ indicates the components' comprehensive correlation.

3.3. Clustering and Evaluation of Skeleton Model Components

3.3.1. Hierarchical Fuzzy Clustering Based on Transfer Closure Method

After quantifying the correlations among the components of the skeleton model, hierarchical fuzzy clustering is performed on the underlying components. This study employs the transitive closure method [35,36] within fuzzy cluster analysis.

A comprehensive correlation matrix M is constructed utilizing the comprehensive correlations between all the components in the skeleton model:

$$M = \begin{bmatrix} z(1,1) & z(1,2) & \cdots & z(1,n) \\ z(2,1) & z(2,2) & \cdots & z(2,n) \\ \cdots & \cdots & z(a,b) & \cdots \\ z(n,1) & z(n,2) & \cdots & z(n,n) \end{bmatrix} \tag{4}$$

where $z(a,b)$ is the comprehensive correlation calculated in Section 3.2.4, n is the number of components in the skeleton model, and M is a symmetric matrix with a principal diagonal element of 1.

By calculating the transitive closure of M, M is transformed into a matrix M^* with transitivity. It is achieved through the computation of fuzzy square:

$$M_{ij}^2 = M_{ij} \circ M_{ij} = \max\{\min[z(i,k), z(k,j)]\},\ k = 1, 2, \cdots, n \tag{5}$$

where max denotes the maximum value from a list of elements, while min denotes the minimum value. When $M^t \circ M^t = M^t$ appears in the process of fuzzy square operations, M^t represents the transitive closure being sought, which is also equivalent to M^*.

Hierarchical fuzzy clustering based on the transitive closure method can evolve multiple skeleton models based on the original skeleton model, laying the foundation for comparing and evaluating skeleton models. Algorithm 1 illustrates the hierarchical fuzzy clustering algorithm for the skeleton model based on the transitive closure method, which includes three main steps: extracting the bottom skeleton model, calculating the comprehensive correlation matrix and its transitive closure, and solving the hierarchical skeleton model. Based on the hierarchical structure of the given skeleton model, the bottom skeleton model components are extracted, while the middle layer and top skeleton models do not participate in subsequent clustering calculations. Utilizing the correlation analysis method of skeleton model components, the comprehensive correlation between components is

calculated to construct the comprehensive correlation matrix M, and the transitive closure M^* is computed. A certain threshold is selected to cluster the elements with high correlations in the matrix M, calculate the average distance between the clustered skeleton model components and other components, update the matrices M and M^*, and repeat this clustering operation until the set number of clustering levels is reached.

The computation complexity of each iteration of Equation (5) is $O(n^3)$, akin to matrix multiplication. According to literature [36], the number of times the transitive closure operation is performed to transform M to M^* does not exceed $\lceil \log_2 n \rceil + 1$.

Algorithm 1 Hierarchical fuzzy clustering algorithm for the skeleton model based on transitive closure method

Input: *Components*, a set of skeleton model components in the form of two-dimensional arrays
Output: The hierarchical skeleton model components obtained by clustering
Function skeletonClustering(*Components*)
Step 1
Create component sets C_{son}, and C_{fa};
for each skeleton component pair (c_i, c_j) in *Components*
  Add c_i to set C_{son};
  if c_j is not None
    Add component c_j to set C_{fa};
  end if
end for
Generate bottom skeleton model component set $C = C_{son} - C_{fa}$;

Step 2
Analyze component correlations in C; //according to Equation (3)
Create a comprehensive correlation matrix M;
Calculate the transitive closure M^*; //according to Equation (5)
After removing duplicates from the elements of M^*, there are t values, which are arranged in ascending order as $0 < \lambda_1 < \lambda_2 \ldots < \lambda_t < 1$, denoted as the set T_λ;

Step 3
Given the maximum clustering level l of the skeleton model;
while $l - 2 > 0$
  for each λ in T_λ
    Set the elements in matrix M^* with values not less than λ to 1, and all other values to 0;
    In the new matrix, the components corresponding to the positions where the elements are 1 are clustered into one category, and the silhouette coefficient (s_λ) of the clustering result is calculated;
  end for
  $\lambda^* = \arg\max s_\lambda$;
  Calculate the distance between the components clustered into one category and other components under the condition of λ^*, take the average values of the corresponding row and column elements in matrix M, update matrix M, and update matrix M^*;
  $l = l - 1$;
end while
Return

3.3.2. Cluster Result Evaluation

The evaluation of clustering results often requires subjective scoring by multiple experts on various criteria. However, this approach is challenging for complex products with highly customized design requirements, such as launch vehicles. Because the design of each product rarely resembles mature historical designs, new products necessitate the experimentation of novel technologies, making it difficult to reference existing products for the design of their skeleton models. Organizing experts for subjective evaluations can result in significant human resource consumption.

Therefore, selecting objective and universally applicable evaluation indicators is of significant importance. Each clustering results in hierarchical fuzzy clustering; that is, the new skeleton model evolved from the original skeleton model, and the silhouette coefficient can be calculated to assess the relative merits of the skeleton model design. This paper emphasizes the refinement of complex product clustering division by adopting a modified silhouette coefficient to evaluate clustering results. The method of calculation is shown in Equations (6) and (7):

$$s(i) = \frac{b(i) - a(i)}{\max\{b(i), a(i)\}} \times \frac{r-1}{r+1} \tag{6}$$

$$s = \text{average}\{s(i)\} \tag{7}$$

where $a(i)$ represents the average distance between component i and all other components within the cluster to which it belongs, that is, the cohesion; $b(i)$ represents the average distance between component i and all components in the nearest adjacent cluster, that is, the separation; r denotes the number of clusters; and $s(i)$ is the silhouette coefficient of component i, which tends to favor clustering results with more clusters. For a skeleton model composed of n components, $1 \leq i \leq n$, s represents the average silhouette coefficient of all components, which is the final metric to evaluate the quality of clustering results. The larger the separation, the smaller the cohesion, and the larger the silhouette coefficient, the better the cluster result. To facilitate more intuitive evaluation results, s undergoes min–max normalization to map it to a scale of 0 to 100.

The relationship between the average distance $a(i)$, $b(i)$, and the correlation values is illustrated in Equations (8) and (9):

$$a(i) = 1 - c(i) \tag{8}$$

$$b(i) = 1 - d(i) \tag{9}$$

where $c(i)$ represents the average correlation of component i with all other components in the cluster to which it belongs, and $d(i)$ denotes the average correlation of component i with all components in the nearest adjacent cluster.

4. Case Study

Taking the skeleton model of a rocket nose cone as the subject, the effectiveness of the proposed method is verified. The rocket nose cone is a typical aerospace product, involving various disciplines such as structure, attitude control, aerodynamics, etc. It employs a full three-dimensional design approach based on a skeleton model. The nose cone skeleton model encompasses not only the installation dimensions and positions of all the equipment inside it, but also crucial interface data between the nose cone and other rocket sections. Designers create the solid three-dimensional model within the constraints of the skeleton model. Therefore, the rationality of the model has a significant impact on subsequent detailed design.

Designers often rely on experience to conduct hierarchical design for the skeleton model. Figure 7 illustrates a practical layered design scheme for the skeleton model of a rocket nose cone. Under the "Rocket nose cone" node, there are two sub-nodes, "Rocket head cap" and "Shell of the cone". The "Shell of the cone" node accommodates all other nodes. The majority of components in this skeleton model have not undergone detailed, layered design based on the product's function and spatial distribution requirements, which can easily lead to confusion in the reference relationships between components and make it difficult to achieve reasonable control of the detailed design assembly model by the skeleton model. Designers require quantitative evidence to assist them in judging the reasonableness of the skeleton model design, which is also the objective of the research presented in this paper.

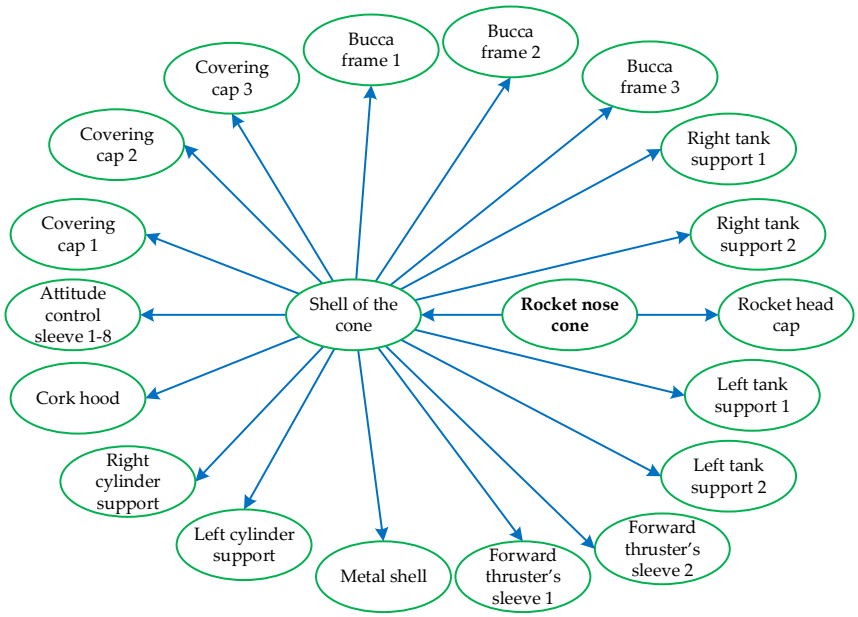


Figure 7. Layered design for the rocket skeleton model based on the experience of designers.

4.1. Correlation Analysis of Components in the Skeleton Model of a Rocket Nose Cone

Based on the knowledge representation models, the associative relationships among nodes in Figure 7 are analyzed, including function, behavior, and structure correlation.

4.1.1. Process and Results of Function Correlation

Through field research into the functions of components described by the designers of the rocket, a function knowledge representation model has been defined, with a portion of the model illustrated in Figure 8. Based on the function knowledge representation model, the function correlation among various components has been analyzed, with some results presented in Table 4. In Table 4, the function type of "Shell of the cone" is "Stabilize", and the function type of "Forward thruster's sleeve 1" is "Position". The function correlation value can be calculated as $0.5 \times 0.8 + 0.5 \times 1 = 0.9$ using Equation (1) and Figure 6. The function correlations between all components are quantified using this method.

Table 4. Analysis of the function correlation of selected components.

Component *A*	Function Type of *A*	Type of Discipline	Component *B*	Function Type of *B*	Type of Discipline	Correlation
Rocket head cap	Stabilize	Dynamics	Shell of the cone	Stabilize	Dynamics	1
Rocket head cap	Stabilize	Dynamics	Forward thruster's sleeve 1	Position	Dynamics	0.9
Shell of the cone	Stabilize	Dynamics	Forward thruster's sleeve 1	Position	Dynamics	0.9

<Function knowledge 1> ::= <Skeleton model component 1> <"Have_Function"> <Function 1>
<Skeleton model component 1> ::= <"Rocket head cap"> <"Bottom Skeleton Model"> <"Composite material">
<Function 1> ::= <"Rectification"> <**Stabilize**> <3> <"Rocket head cap is used to maintain a reasonable aerodynamic shape of the rocket"> <Dynamics>

<Function knowledge 2> ::= <Skeleton model component 2> <"Have_Function"> <Function 2>
<Skeleton model component 2> ::= <"Shell of the cone"> <"Middle Layer Skeleton Model"> <"Von-Karman cone">
<Function 2> ::= <"Rectify and maintain shape"> <**Stabilize**> <3> <"Rectification, shape maintenance, and load-bearing, providing installation space for instruments"> <Dynamics>

<Function knowledge 3> ::= <Skeleton model component 3> <"Have_Function"><Function 3>
<Skeleton model component 3> ::= <"Forward thruster's sleeve 1"> <"Bottom Skeleton Model"> <"Providing separation force">
<Function 3> ::= <"Install forward thruster 1"> <**Position**> <3> <"The sleeve is used to ensure a reasonable installation angle for the forward thruster 1"> <Dynamics>

Figure 8. Function knowledge representation of the rocket nose cone's skeleton model.

4.1.2. Process and Results of Behavior Correlation

Behavior correlation analysis necessitates clarifying the primary energy, signal, and material connections among components within the skeleton model. The studied skeleton model does not encompass cables, sensors, or gas pipelines, thus primarily exhibiting energy connections with minimal material and signal connections. As illustrated in Figure 9, the behavior correlation of components can be ascertained through behavior knowledge representation. The behavior correlation of certain components of the nose cone is presented in Table 5.

<Behavior knowledge 1> ::= <Skeleton model component 1> <Behavior 1> <Skeleton model component 2>
<Skeleton model component 1> ::= <"Forward thruster's sleeve 1"> <"Bottom Skeleton Model"> <"Providing separation force">
<Skeleton model component 2> ::= <"Metal shell"> <"Bottom Skeleton Model"> <"Von-Karman cone">
<Behavior 1> ::= <"Forward push separation"> <Energy Connection> <0.8> <"Ignition occurs during the separation of the rocket nose cone, providing a brief separation force that enables the nose cone to detach from the satellite cabin">

<Behavior knowledge 2> ::= <Skeleton model component 3> <Behavior 2> <Skeleton model component 2>
<Skeleton model component 3> ::= <"Attitude control sleeve 1"> <"Bottom Skeleton Model"> <"The component to install the attitude control thrust chamber ">
<Skeleton model component 2> ::= <"Metal shell"> <"Bottom Skeleton Model"> <"Von-Karman cone">
<Behavior 2> ::= <"Attitude control"> <Energy Connection> <0.8> <"During the flight of the rocket, collaborating with other attitude control sleeves to accomplish the rocket's attitude control">

<Behavior knowledge 3> ::= <Skeleton model component 2> <Behavior 3> <Skeleton model component 4>
<Skeleton model component 2> ::= <"Metal shell"> <"Bottom Skeleton Model"> <"Von-Karman cone">
<Skeleton model component 4> ::= <"Left tank support 1"> <"Bottom Skeleton Model"> <"Support the storage tank 1 together with the right tank support 1 ">
<Behavior 3> ::= <"Support"> <Energy Connection> <0.8> <"The metal shell provides stable support for the storage tank 1 through the left and right storage tank support">

Figure 9. Behavior knowledge representation of the rocket nose cone's skeleton model.

Table 5. Analysis of the behavior correlation of selected components.

Component *A*	Component *B*	Behavior Type	Correlation
Forward thruster's sleeve 1	Metal shell	Energy connection	0.8
Attitude control sleeve 1	Metal shell	Energy connection	0.8
Metal shell	Left tank support 1	Energy connection	0.8

4.1.3. Process and Results of Structure Correlation

The definition of structure correlation involves the analysis of contact types, joint types, and geometric relationships of the rocket nose cone's skeleton model. Regarding contact

types, since the shape and internal structure components of the head cover skeleton model are expressed by surfaces or planes, lacking three-dimensional solid characteristics, line contacts or surface contacts between components such as the metal shell, bucca frame, and covering cap primarily exist. The main joint types in rocket products include riveting, screw joint, and bonding. All major components are fixed to the metal shell through riveting to reduce weight, with only the bucca frame, covering cap, and head cap, which require detachability, adopting the screw joint. Regarding geometric relationships, there are strict restrictions on the spatial distribution of eight attitude control sleeves and two forward thruster's sleeves. Due to the rigorous requirements of the rocket for mass distribution, tank supports and cylinder supports need to be centrally symmetrical. As shown in Figure 10, the structure correlations of components can be obtained through the structure knowledge representation of the rocket nose cone's skeleton model. The structure correlations of some components are shown in Table 6, where contact types, joint types, and geometric relationships have corresponding correlation values. The composition relationship is necessary for establishing a multi-level skeleton model without defining correlation values.

<Structure knowledge 1> ::= <Skeleton model component 1><Combined component relationship 1><Skeleton model component 2>
<Skeleton model component 1> ::= <"Rocket head cap"><"Bottom Skeleton Model"><"Composite material">
<Skeleton model component 2> ::= <"Metal shell"><"Bottom Skeleton Model"><"Von-Karman cone">
<Combined component relationship 1> ::= <Basic component relationship 1><Basic component relationship 2>
<Basic component relationship 3>
<Basic component relationship 1> ::= <Unilineal Contact><0.4>
<Unilineal Contact> ::= "Surface and Surface"
<Basic component relationship 2> ::= <Detachable Joint><0.4>
<Detachable Joint> ::= "Screw Joint"
<Basic component relationship 3> ::= <Rigorous Geometric Relationship><0.8>
<Rigorous Geometric Relationship> ::= "Coaxiality"

<Structure knowledge 2> ::= <Skeleton model component 1><Basic component relationship 4><Skeleton model component 3>
<Skeleton model component 1> ::= <"Rocket head cap"><"Bottom Skeleton Model"><"Composite material">
<Skeleton model component 3> ::= <"Rocket nose cone"><"Top Skeleton Model"><"The skeleton model of the entire rocket nose cone">
<Basic component relationship 4> ::= <Composition Relationship>
<Composition Relationship> ::= "Belongto_subsystem"

Figure 10. Structure knowledge representation of the rocket nose cone's skeleton model.

Table 6. Analysis of the structure correlation of selected components.

Component *A*	Component *B*	Structure Relation	Correlation
Rocket head cap	Metal shell	Unilineal contact ("Surface and Surface")	0.4
Rocket head cap	Metal shell	Detachable joint ("Screw Joint")	0.4
Rocket head cap	Metal shell	Rigorous geometric relationship ("Coaxiality")	0.8
Rocket head cap	Rocket nose cone	Composition relationship	/
Forward thruster's sleeve 1	Metal shell	Unilineal contact ("Surface and Surface")	0.4
Forward thruster's sleeve 1	Metal shell	Weak fixed joint ("Riveting")	0.6
Forward thruster's sleeve 1	Metal shell	General geometric relationship	0.6
Metal shell	Rocket nose cone	Composition relationship	/

4.2. Evaluation of the Rocket Nose Cone's Skeleton Model

Based on the analysis of the correlation of components in the rocket nose cone's skeleton model, the lowest-level components are extracted for hierarchical fuzzy clustering, resulting in a more rational skeleton model design. A quantitative evaluation is conducted

based on the differences between the existing skeleton model and the rational results. According to the methods described in Section 3, a prototype system for evaluating the skeleton model has been developed. By filling in the function information of components from the existing skeleton model into a table, the structure information tables (contact info, joint info, and geometric info) and the behavior information table are imported. Then, a quantitative evaluation of the rationality of the skeleton model is conducted. The evaluation score of the rocket nose cone's skeleton model is calculated, and two optimized design results under the provided skeleton model are displayed on the results page, as illustrated in Figure 11.

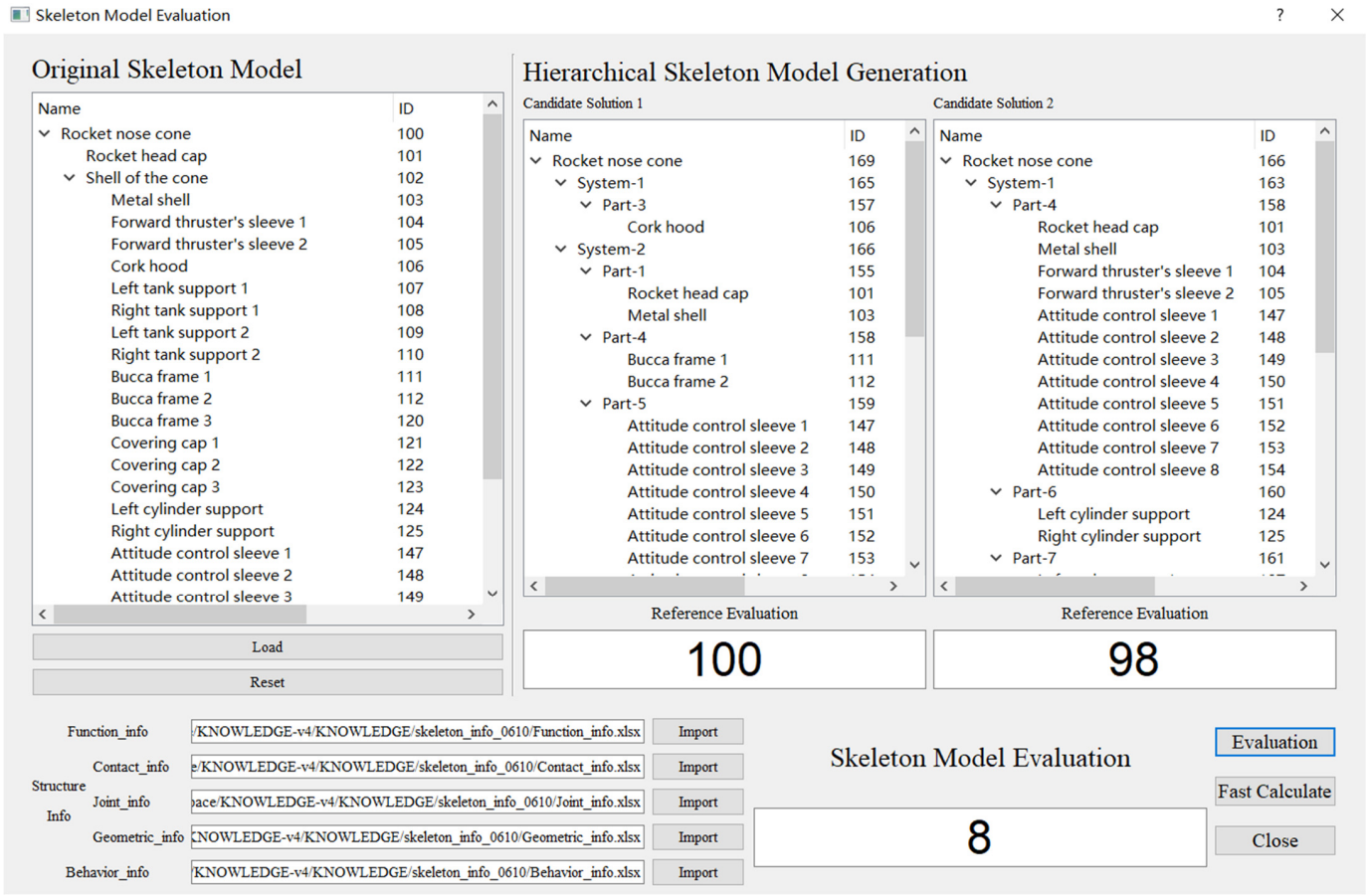


Figure 11. The hierarchical clustering results and evaluation outcomes of the skeleton model.

Compared to the given skeleton model, two more reasonable outcomes are obtained through hierarchical fuzzy clustering of components. The hierarchical modeling result of candidate solution 2 is shown in Figure 12a, where some node names are designated as "System-1" and "Part-1" by default, necessitating manual assignment of names with actual engineering significance, such as "Main structure". Figure 12b illustrates the ideal skeleton model defined by rocket design experts. By comparing Figure 12a,b, it is observed that the ideal design identified by the experts exhibits good consistency with the design results of the skeleton model generated by the algorithm presented in this paper. This indicates that the designs with high scores evaluated by the algorithm in this paper closely approximate the ideal designs recognized by experienced experts, and the scoring results align with the perceptions of corporate designers. Consequently, this paper's method and prototype system achieved the quantitative evaluation of complex product skeleton models.

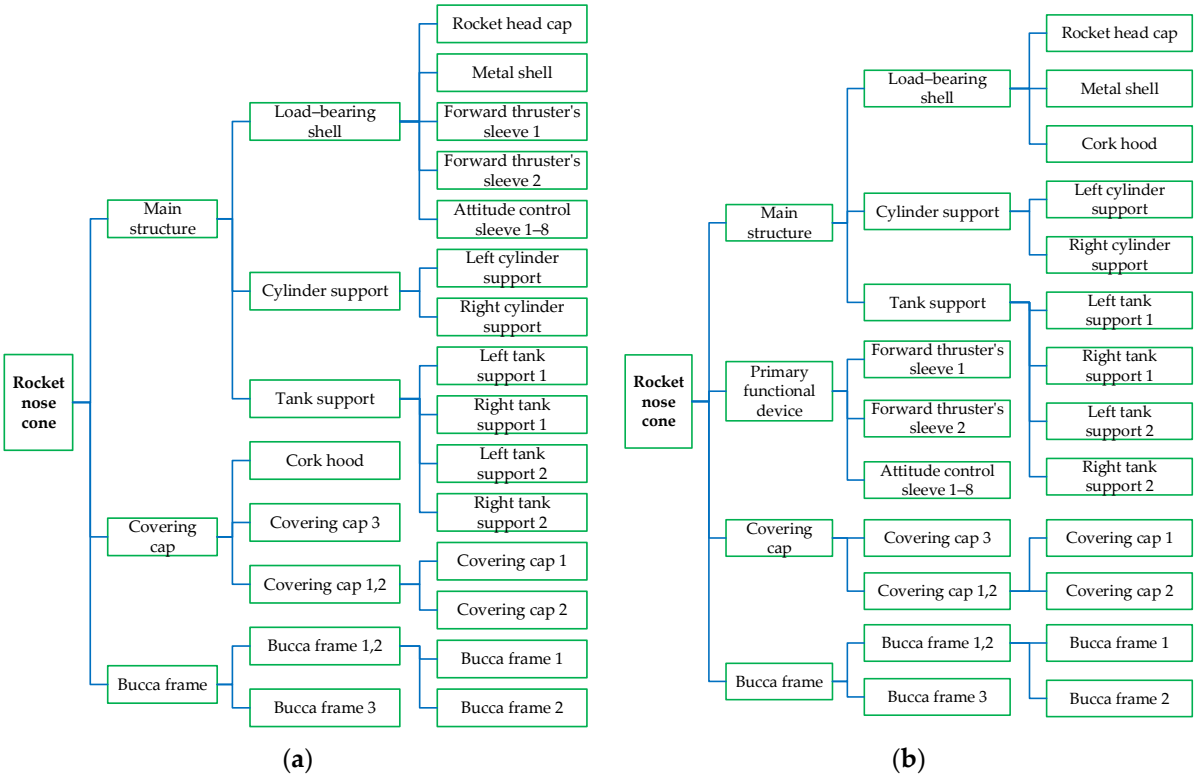


Figure 12. Comparison of the skeleton model generated by the algorithm versus rocket experts. (**a**) The skeleton model generated by the algorithm in this paper. (**b**) The ideal skeleton model defined by rocket experts.

5. Discussion

The complexity of modern product design is escalating, with products such as rockets and automobiles featuring intricate surfaces and a vast array of components. Therefore, introducing the skeleton model in the early design stages becomes crucial for modeling key design constraints and transmitting critical design parameters. Complex products necessitate complex skeleton models, primarily generated based on the experience of designers. For highly complex skeleton models, it is challenging for designers to accomplish a satisfactory design scheme through mental simulation in a short period. The original failed design of the rocket nose cone's skeleton model cited in this article illustrates this point. Utilizing scientifically quantified methods to evaluate the rationality of the skeleton model is a necessary supportive measure for defining a well-designed skeleton model in the early stages of design.

The paper introduces a skeleton model evaluation method that aligns with the cognitive habits of designers. The design of the skeleton model for complex products is hierarchical, with the hierarchy based on the closeness of relationships between different components. The natural cognitive habit is that components with close relationships belong to the same parent node in the skeleton model, while components with distant relationships should belong to different parent nodes. The skeleton model design is based on the closeness of component relationships, and the rationality of the skeleton model design is quantitatively evaluated based on the correlation between nodes in the model tree. The research analyzes the hierarchical characteristic of the skeleton model, selects the function, behavior, and structure connections that can be considered when designing the skeleton model, and proposes quantitative methods for different correlations.

This study utilizes the transitive closure analysis method from fuzzy mathematics to perform hierarchical fuzzy clustering on the various bottom components of the skeleton

model. Through this process, multiple distinct skeleton models can be generated. These generated skeleton models, along with the original design, should all be accompanied by a metric for quantitatively assessing the rationality of the skeleton model design. This study opts for the silhouette coefficient as the indicator for the quantitative evaluation of rationality. A larger silhouette coefficient indicates a greater degree of separation among child nodes under the different parent nodes while indicating a lesser degree of cohesion among child nodes of the same parent nodes, thus aligning with the ideal outcomes of the skeleton model design. This study clarifies the mathematical metrics for evaluating the skeleton model, which has not been achieved in existing skeleton modeling software and academic research. Therefore, the method studied in this paper is innovative.

However, this study also has certain limitations. On the one hand, the currently proposed methods for describing knowledge in skeleton models lack sufficient flexibility and scalability. For instance, the situation where a component possesses multiple functions within the function description knowledge model has not been adequately addressed. Since no content regarding the definition of skeleton model knowledge has been found in existing literature, there is certainly room for optimization of the method proposed in this paper. On the other hand, it is challenging to handle situations where the number of components in the skeleton model is in the thousands, as the time complexity of the algorithm exceeds $O(n^3)$. In fact, time complexity also prompts reflection on how the academic community defines skeleton models and complex products. Only after these concepts are clarified can we provide answers regarding how to handle the number of components.

6. Conclusions and Future Works

Based on knowledge modeling in function, behavior, and structure, a quantitative description of component connection in the skeleton model is achieved, and a comprehensive correlation is defined using a weighted sum method. Based on quantifying the comprehensive correlation of function, behavior, and structure, a clustering analysis of skeleton model components is realized through the transitive closure method. Subsequently, multiple skeleton models are generated based on the given skeleton model. The rationality of the automatically generated hierarchical skeleton model is evaluated using the silhouette coefficient and compared with the original design, achieving a quantitative evaluation of the relative superiority and inferiority of the skeleton model. This method has been applied to designing the skeleton model for the nose cone of a specific type of rocket, realizing the quantitative evaluation of the skeleton model.

Further research will contribute to enhancing the theoretical and practical significance of this paper. On one hand, there is still room for improvement in the architecture of complex product knowledge models. Defining a knowledge modeling framework that is easily extensible, storable, and dynamically updatable is crucial to represent the multi-domain knowledge of technology-intensive products during the iterative refinement process across multiple teams. This is essential for better adapting to the design and improvement of various complex product skeleton models in industrial practice. On the other hand, regarding the multifactorial joint decision making issues addressed in this paper, the initial weight selection is often based on expert experience or methods such as the analytic hierarchy process (which can also be subjective). However, with the accumulation of design cases, introducing a dynamic weight adjustment mechanism is a viable approach to ensure the rationality of decision making.

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Data Availability Statement: The comprehensive correlation matrix M and its transitive closure M^* are available on GitHub at https://github.com/scliu13/HFCluster (accessed on 27 November 2024).

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Helicopters are primarily classified into single-rotor and twin-rotor helicopters based on their structural forms. By equipping them with different functional devices, they provide services in various industries, such as military, firefighting, and transportation. Figure A1 depicts the hierarchical design of the skeleton model for a certain helicopter's main structure, which primarily includes the fuselage and landing gear. Utilizing the method and tool presented in this paper to evaluate this skeleton model, a new skeleton modeling result is obtained, as shown in Figure A2. Figure A3 presents the evaluation result of the skeleton models in Figures A1 and A2. The skeleton model in Figure A1 scores 64 points, while the one in Figure A2 scores 100 points. Compared to Figure A1, the skeleton model in Figure A2 separates the engine firewall and the horizontal tail control from the fuselage, as the former requires frequent disassembly and inspection, while the latter belongs to the attitude control system. Additionally, the helicopter's top and bottom cowling do not directly interact, but are connected through the fuselage mid-section, transition section, and cockpit. Therefore, the top and bottom cowling should be separated. The result from Figure A2 is more reasonable than that from Figure A1, which is reflected in the scores given in Figure A3.

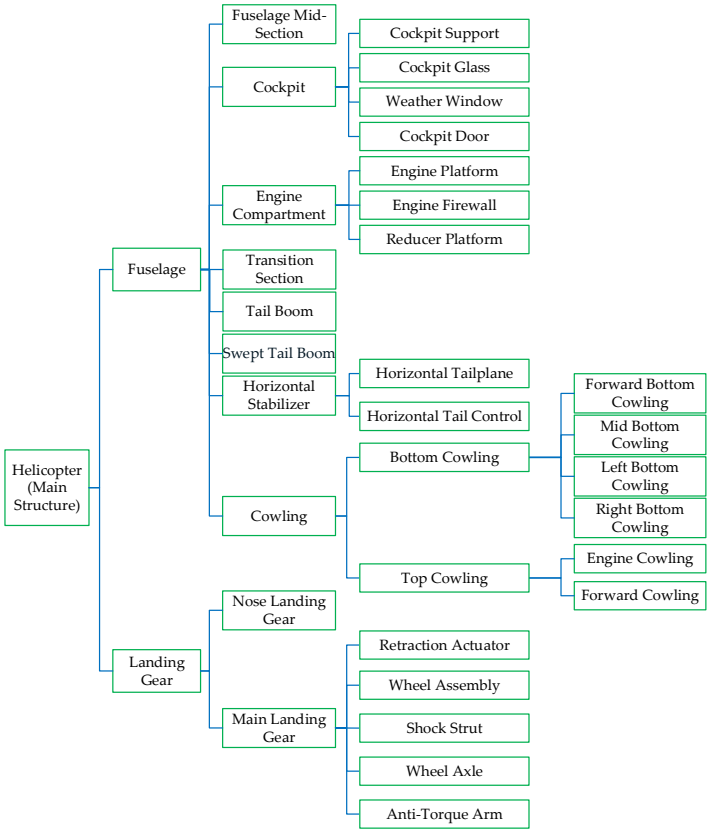


Figure A1. The hierarchical design of the skeleton model for the helicopter's main structure based on experience.

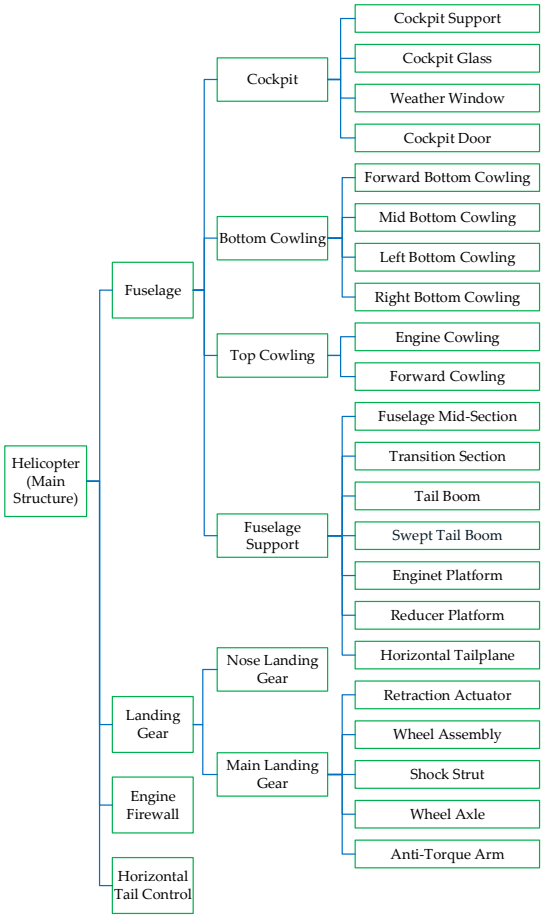


Figure A2. The skeleton model for the helicopter generated by the algorithm in this paper.

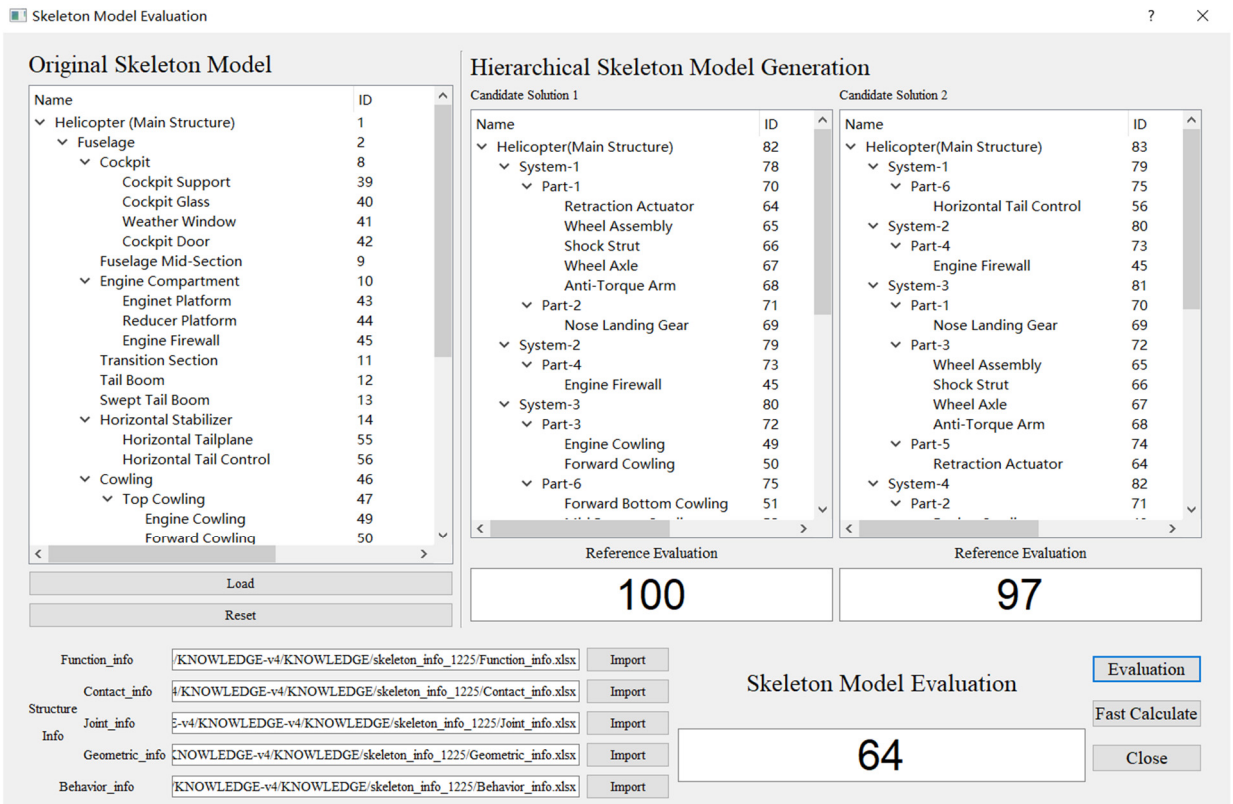


Figure A3. The hierarchical clustering results and evaluation outcomes of the skeleton model for the helicopter's main structure.

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