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Clustering Collaborative Method for Complex Product Hierarchical Modules based on HDSM and SysML

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Abstract

The design and development process of complex product is a multi-disciplinary collaborative process, which requires the cooperation of distributed teams. However, complex product involves complex models and specifications but poor interoperability, resulting in high equipment support costs, low support efficiency and equipment utilization. According to the characteristics of complex product design and development, in order to improve the efficiency of modeling and simulation for complex product collaborative design and development process, clear and trace the relationship between the elements of design activities, then reduce the repetitive construction caused by design iteration and uncertainty in product design, a Clustering Collaborative Method for Complex Product Hierarchical Modules Based on HDSM and SysML is proposed. This method is aimed at different stages of complex product design and development, and uses different technical methods of HDSM, directed graph and SysML to solve the problems in the modeling process of complex product design and development. Hierarchical analysis of design activities through HDSM during the design process can significantly reduce the degree of modeling repeatability. Using the quantitative analysis of directed graphs, the uncertainty caused by subjective modeling in the HDSM method can be reduced. Using SysML for modularized graphical description can enhance the visibility, reusability and consistent expression of models, and improve the efficiency of product modeling and development. An engineering case study demonstrated that the proposed method are effective and efficient for the the interoperability and utilization of complex product design modules.

Keywords

Directed Graphs; SysML; HDSM; Complex Product Development.

1. Introduction

Nowadays, personal customers and users' requirements of complex product market are transformed to specific information taken up with manufacturing complex product during the design process [1, 2]. As shown in Figure 1(a), the design and development of complex product generally requires a synergy of multi-disciplinary development team. When applying simulations into the complex products development, Multi-disciplinary Collaborative Simulation (MCS) is assigned to integrate simulation models and decision-making process, which aims to support the collaboration between members of the development team [3, 4]. The solution proposed aims to address a specific issue on representing an integrated and collaborative simulation space. To give an overview of Integrated and Collaborative Simulation Management (ICSM) scheme as well as its key components [3, 4], a framework is shown in Fig.1 (a). In the outsides of the figure, Collaborative design team and users with different roles can participate in the collaborative design environment, meanwhile in the center of the figure, product design lifecycle stages of knowledge management are in connection with specific design activities. As for every activities, explicit knowledge of simulation models and tacit

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knowledge of decision-making process is connection with an integrated simulation models, namely Engineering-APPs [5].

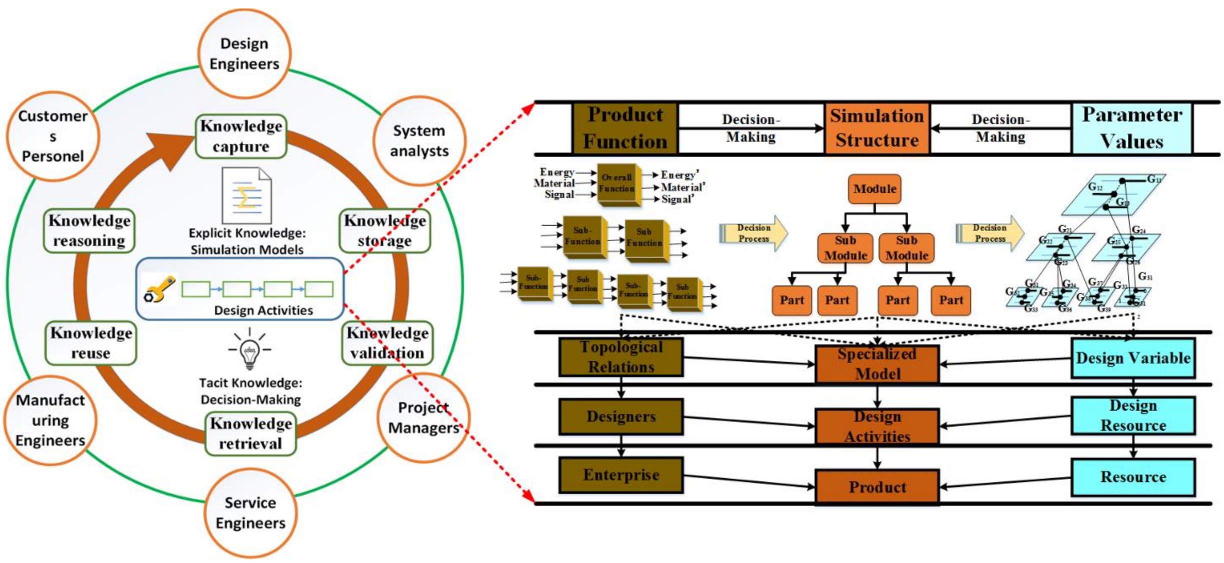
Before developing the integrated simulation models, collaborative design process of complex product should be taken into special consideration [4]. According to the top-down design principle, the complex product design process based on the product topological function and physical structure is illustrated in Fig.1 (b). As described in Fig.1 (b), it should be determined first the function set according to the customers' design demands [6]. Then each function can be further divided into a set of sub-functions and sub-flows. When the overall functions of complex product are decomposed zigzag, simulation modules are also designed or selected from an available module base [7]. The simulation module could be further decomposed into a set of sub-modules and parameters whose values should to be determined.

As shown in Fig.1, when analyzing the design and development process of complex products, it shows the characteristics of cross-domain multi-discipline, distributed collaborative and model-based multi-coupling. As the core content of complex product development process, product distributed collaborative design is responsible for dynamically managing product development nodes, organizing multidisciplinary, cross-domain and dynamically evolving product design knowledge, and coordinating design constraints and conflicts of all parties, which is the key factors for success [8, 9]. As an important part of the current and future product systems, complex product has the following common characteristics in the structure of the developing process:

(1) The design and development process of complex product generally adopts the "decomposition-integration" design paradigm, then allocates design resources and design services in a fine-grained manner.

(2) The design and development process of complex product is accompanied by the continuous iteration of tasks and activities at different developed levels, and the process of design activity iteration is always accompanied by the data interaction of different disciplines and components to achieve the best design scheme.

(3) The complex product development process is accompanied by design conflicts at different levels, such as index conflicts between discipline systems, resource utilization conflicts and so on, requiring designers to participate in a large number of design decisions.



（a）Collaborative Simulation Management （b）The top-down design process

Fig. 1 The design framework of complex product development

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2. Hierarchical Decomposition Optimization Method for Complex Product based on HDSM

The essence of the logical transfer relationship between the design activities in the complex product design and development process is the reflection of the data dependency transfer between the research and development activities at various levels [10]. In order to analyze the data dependencies between complex product design activities, this section first proposes an analysis method based on the Hierarchical Design Structure Matrix (HDSM). First, establish a hierarchical system architecture for the entire complex product developing process. Different hierarchical systems correspond to a Design Structure Matrix (DSM) architecture for a set of design activities [11]. As shown in Fig 2, the vehicle chassis is taken as an example to describe the hierarchical decomposition optimization model of complex product based on HDSM. The initial column and initial row define the design component corresponding to the design activity. In each design structure matrix DSM, the diagonal element C defines the index parameters, constraint interval and algorithm simulation model in the corresponding design activity, and the element I/O defines the index parameter feedback between design activities. The off-diagonal elements define the input and output parameter design templates of the design activities, and construct the external design interface of the design activities [12].

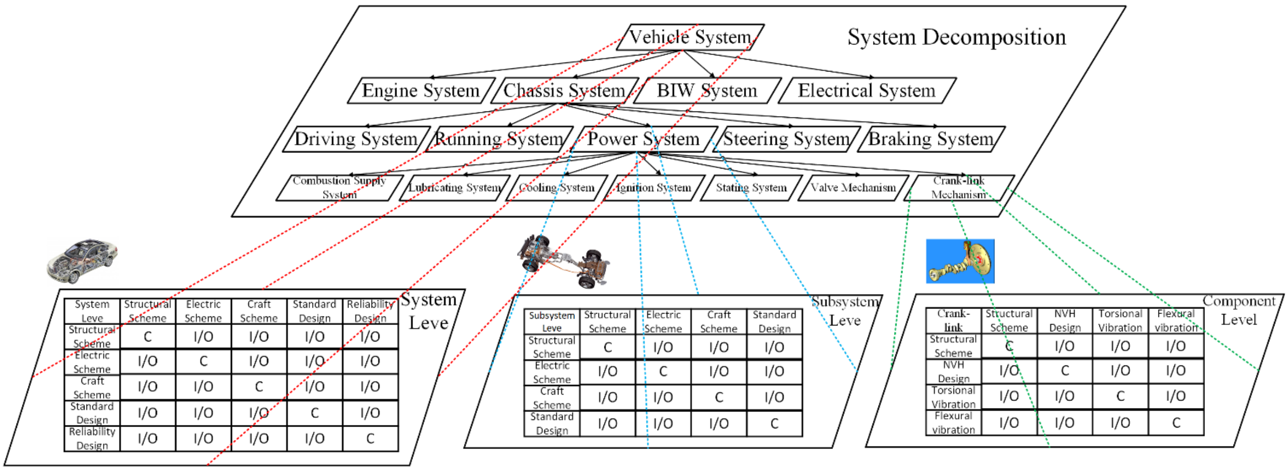

Fig. 2 The hierarchical decomposition optimization model of complex products based on HDSM

As shown in Fig 2, the hierarchical decomposition model of the system obtains modules with different granularities at different levels, and each granularity module is mapped to a corresponding DSM design structure matrix. In the research and development process of the vehicle chassis, System-level DSM design activities include system-level design and development activities such as Overall Structural Scheme Design, Overall Electrical Scheme Design, Overall Craft Scheme Design, Standardization Design and Reliability Design; One of the subsystem-level DSM design activities includes subsystem-level design and development schemes such as structural design scheme, electrical design scheme, process design scheme, standardized design scheme and reliability design scheme; A component-level DSM design activity in this subsystem includes design activities such as structural design, NVH design, torsional vibration design, and flexural vibration design. In conclusion, the HSDM hierarchical design structure matrix defines the division structure of complex product designs, the data dependencies of design activities, and the mapping relationship between the developing process and DSM.

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2.1. Hierarchical Design Structure Matrix (HDSM)

Hierarchical design structure matrix HDSM is improved and developed on the basis of design structure matrix DSM. The design structure matrix theory was proposed by Steward [11] in 1981. This theoretical model expresses the coupling relationship and iterative process in the complex product development process in the form of a structure matrix, which provides a powerful analysis tool for reducing the complexity of complex product development tasks. As shown in Fig.3(a), the design structure matrix is a square matrix of order n whose dimensions represent the number of design activities, and the initial rows and columns of the matrix correspond to a set of identical design activities. Elements in the matrix where rows and columns intersect represent the degree of dependency information between design activities. The elements below the diagonal represent forward feedback of information, and the upper elements represent backward feedback of information.

As shown in Fig.3(a), in the binary DSM:

$$a_{ij} = \begin{cases} 0 & \textit{Indicates that there is no information dependency between } A_i \textit{ and } A_j \\ 1 & \textit{Indicates that there is an information dependency between } A_i \textit{ and } A_j \end{cases} \tag{1}$$

In Fig.3(b), by analyzing the correspondence between the directed graph and the design structure matrix, the product design structure adjacency matrix can be transformed into an adjacency matrix in the product directed graph.

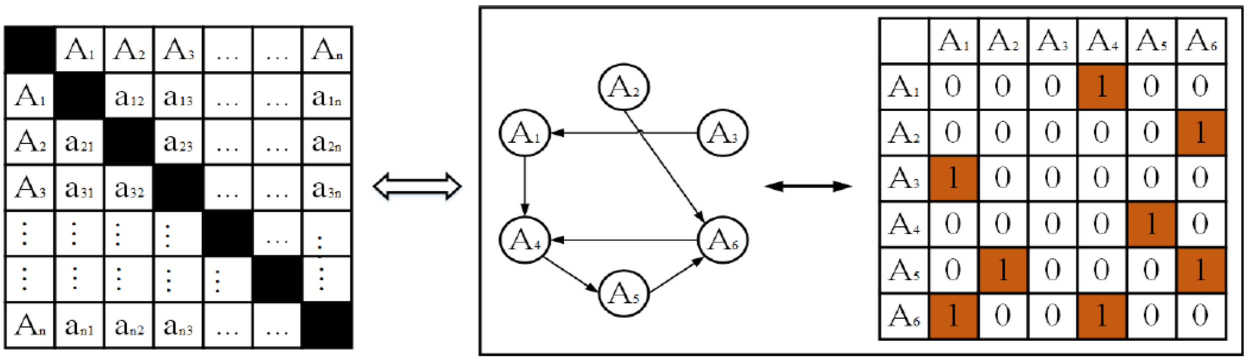


Fig. 3 Binary DSM Structure Diagram

As the hierarchical structure of modern complex products becomes more and more abundant, the traditional design structure matrix DSM can no longer meet the current product design requirements. It becomes extremely difficult to identify the connections between the elements of the matrix. The HDSM hierarchical design structure matrix is developed under this situation. It generates each hierarchical structure matrix by decomposing the hierarchical relationship layer by layer. Each structure matrix form can be expressed as an interrelated sub-matrix, and its form is expressed as follows:

$$F_0 = \{M_1, M_2, M_3, \cdots, M_i\}, i \in N \tag{2}$$

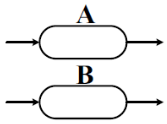
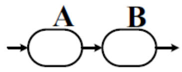
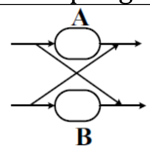
In the formula, F_0 is the overall hierarchical design structure matrix of complex products, and M_i is the submatrix of matrix F_0.

Each level model obtained through the hierarchical design structure matrix HDSM is composed of different fine-grained design activities and their dependencies. The deeper the level, the smaller the fine-grained activity, and the greater the influence of the upper-level design structure. There is a structural relationship between the levels of inheritance and expansion.

2.2. Information Interaction Model among Design Activities

The information interaction in the collaborative development of complex product design is the transfer of data, information and knowledge in the content of various design activities among the stakeholders of product development. By analyzing the relationship of information transmission among design activities in product collaborative design and development, the information transmission structure among different design activities can be divided into three forms: parallel, serial and coupling. Its active structure type and its Boolean binary DSM structure matrix are shown in Table 1. In Table 1, A and B correspond to different design activities respectively. If there is no information transmission from A to B or B to A, the elements in the second-order DSM structure matrix constructed by design activities A and B are all 0. If there is an information transfer relationship between A and B, the element in the lower left corner of the second-order DSM structure matrix is 1. If there is an information transfer relationship between B and A, the element in the upper right corner of the second-order DSM structure matrix is 1, and the element on the diagonal line is 1. Uniformly set to 0, indicating that the design activity itself has no information transfer relationship.

Table 1. Boolean Matrix in Active Structure Model

Relationship	parallel			serial			coupling		
Graphical Representation									
		A	B		A	B		A	B
	A	0		A	0		A	0	1
	B		0	B	1	0	B	1	0

3. Hierarchical Cluster Analysis of Product Structure

When analyzing the product hierarchy design matrix, it can be found that the design nodes in the directed graph can well correspond to the various design activities in HDSM. According to the theoretical analysis of the graph theory for directed graph [13], the hierarchical design structure matrix can map to the adjacency matrix. The following definitions are given below:

Definition 1: A given set of design activities is $E=\{e_1,e_2,\cdots,e_i,\cdots e_j,\cdots,e_n\}$, the set of relationships among design activities is $R=\{r_1,r_2,\cdots,\cdots,r_m\}$,then the elements a_{ij} of the n-order adjacency square matrix A for the directed graph $G=<E,R>$ is:

$$a_{ij}=\begin{cases}0 & Indicates\ that\ e_i\ and\ e_j\ are\ not\ related\\ 1 & Indicates\ that\ e_i\ and\ e_j\ are\ related\end{cases} \tag{3}$$

Definition 2: Each node of a given directed graph $G=<E,R>$ has an association order from e_1 to e_n, then the square matrix of order n $P=(p_{ij})_{n\times n}$, as for this matrix:

$$p_{ij}=\begin{cases}0 & Indicates\ that\ there\ is\ at\ least\ one\ non-zero\ length\ path\ from\ e_i\ to\ e_j\\ 1 & Indicates\ that\ there\ is\ no\ one\ non-zero\ length\ path\ from\ e_i\ to\ e_j\end{cases} \tag{4}$$

Then the matrix P is called the reachability matrix of the directed graph G.

Definition 3: Given that P^T is the transpose matrix of the reachability matrix P, and the matrix Q is the strong connectivity judgment matrix of P, then:

$$Q = P \cap P^T \tag{5}$$

When analyzing the reachability matrix algorithm, if the non-zero elements of the i-th row of the matrix Q are in the $j_1, j_2, \cdots, j_k$ columns, then the nodes e_{j1}, $e_{\mathrm{j}2}$, ⋯, e_{jk} are in a strongly connected branch. According to graph theory, the design activities in the same “strongly connected” are most related and can be clustered into one class.
Meanwhile, by analyzing the reachability matrix P, the reachable set $\mathrm{R}(e_\mathrm{i})$ and the antecedent set $\mathrm{A}(e_\mathrm{i})$ of e_i can be obtained. The reachable set $\mathrm{R}(e_\mathrm{i})$ is composed of all elements whose value is 1 in the same row as the element e_i in the reachable matrix, the antecedent set $\mathrm{A}\ (e_\mathrm{i})$ is composed of all the elements in the same column of the reachable matrix and the element e_j whose value is 1, then:

$$R(e_\mathrm{i}) = \{e_\mathrm{i} | a_{ij} = 1\} \tag{6}$$

$$A(e_\mathrm{j}) = \{e_\mathrm{j} | a_{ij} = 1\} \tag{7}$$

Then the intersection $M(e_\mathrm{k})$ of the reachable set $R(e_\mathrm{i})$ and the antecedent set $A(e_\mathrm{j})$ is:

$$M(e_\mathrm{k}) = R(e_\mathrm{i}) \cap A(e_\mathrm{j}) \quad k = 1,2,\cdots,n \tag{8}$$

Definition 3: Suppose there exists $R(e_\mathrm{i})$ such that the following equation holds:

$$M(e_\mathrm{k}) = R(e_\mathrm{i}) = R(e_\mathrm{i}) \cap A(e_\mathrm{j}) \tag{9}$$

Then let the set M = $M(e_\mathrm{k})$, M is the highest level element set of the system, and so on, on the premise of removing the highest element set, the secondary element set can be continuously obtained. By synthesizing the above methods, the overall hierarchical division module structure of the complex product system can be obtained.

4. Expression Method of Complex Product Design based on SysML

The significance of the module division of complex product design activities is to support the development of modules at different levels for complex products, and to intuitively express the clustering pedigree of complex products. The above method can effectively analyze and optimize the complex product design activity module when using the hierarchical design structure matrix, and obtain the dynamic pedigree of the hierarchical complex product, but it still lacks a modular and unambiguous graphical expression to support the development of subsequent products. The SysML-based model language highlights the consistency, reusability and graphics of the model in the actual modeling process, and can convert the product lineage obtained above into a unified and standardized SysML model stored in the computer for analysis of complex systems, design and verification. The graphical model of SysML modeling language is shown in Fig.4. SysML can be divided into requirements diagram, behavior diagram and structure diagram. These three types of graph models are based on UML and extend the 9 kinds of graph models shown in Fig.4. These 9 kinds of model diagrams can respectively represent the requirements, structure, behavior and parameter transfer relationship of product development.

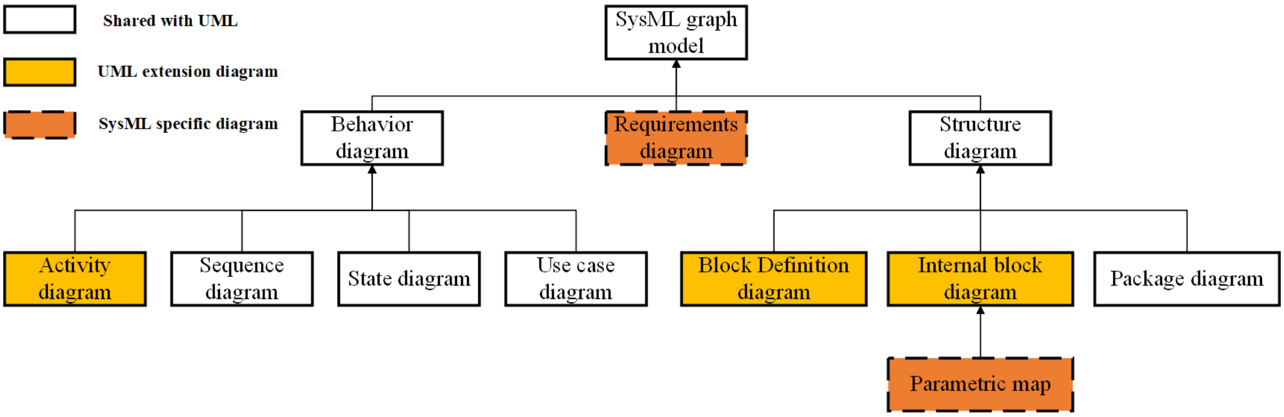


Fig. 4 SysML graph model

As shown in Table 2, in the requirements analysis stage and functional analysis stage, the requirement diagram and use case diagram in the SysML modeling language can be used to express the design analysis process from design requirements to design indicators; in the design synthesis stage, SysML can be used In the modeling language, the module definition diagram, sequence diagram, activity diagram, state diagram, and parameter diagram represent the relationship constraints such as parameters, sequences, and structures between design activities; in the system verification stage, the state diagram and the state diagram in the SysML modeling language can be used. Sequence diagrams simulate the rationale for complex product development processes. Therefore, this chapter can use the SysML modeling language to express and describe the entire development and design activities of complex products.

Table 2. Correspondence between design phases and product design characterization

Serial Number	Design Phase	Model Diagram Representation
1	Requirements analysis, functional analysis	Requirements diagram, use case diagram
2	Detailed Integrated Design Phase	Module definition diagram, Sequence diagram, Activity diagram, State diagram
3	System Verification Phase	State diagram, Sequence diagram

5. Case Verification

The effectiveness and feasibility of the proposed method in the detailed design stage are verified by the analysis of the engine-level development process. The rotary piston engine of the automobile chassis is a complex product that is interdisciplinary and multidisciplinary. This paper takes the hierarchical development process of the rotary piston engine as an example to verify the case. The specific process is as follows:

1) The design of a product begins with a requirement analysis. As shown in Fig.5, the design and development requirements of rotary piston engines include four aspects: functional requirements, performance requirements, structural requirements and dimension requirements, and each requirement can be further subdivided into several requirements, and the requirements specification can be obtained according to the requirement analysis.

2) Due to the system complexity of the rotary piston engine system itself, the design activity relationship is transformed through the hierarchical design structure matrix as shown in Fig.6.

This case selects a small part of its modular design for characterization. As shown in Table 3, the selected hierarchical modules are: vehicle system, remote control vehicle subsystem, intelligent bearing platform subsystem, platform chassis system, information bearing platform, powertrain, power system, transmission system, crank link mechanism, body design, flywheel design, piston selection, piston ring selection, connecting rod design, crank design, bearing pad design and son on. By analyzing the relationship between vehicle design and rotary piston engine at various levels, the adjacency matrix is used to represent each level in the table. Then design the information transfer relationship of the activity module.

3) Table 4 expresses the reachability matrix transformed from the adjacency matrix, which describes the degree to which a path of several steps between the factors affecting the vehicle performance in the complex system of vehicle design can be reached. By analyzing the strongly connected judgment matrix, the original matrix level display diagram shown in Table 5 can be obtained.

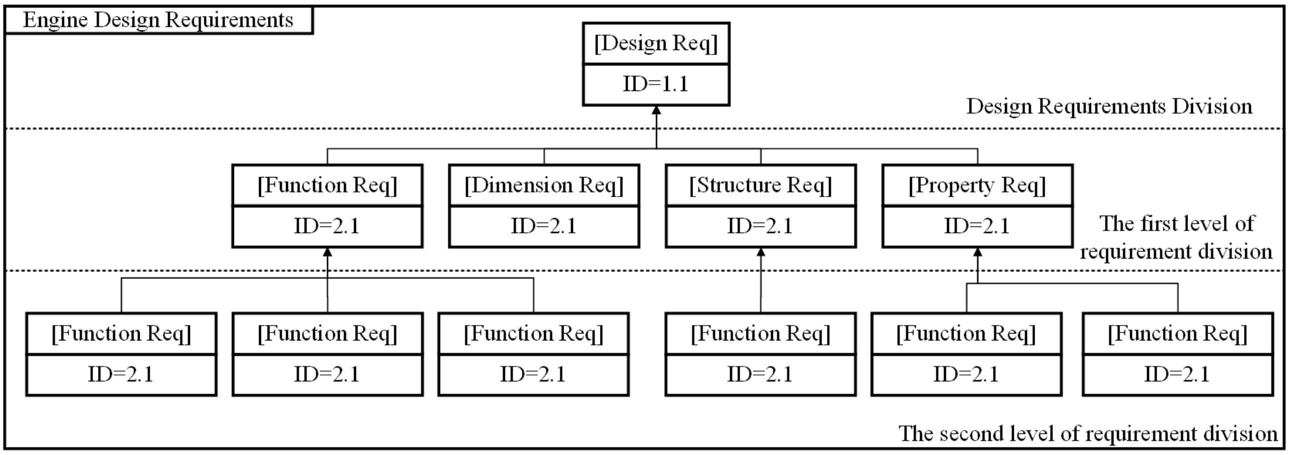
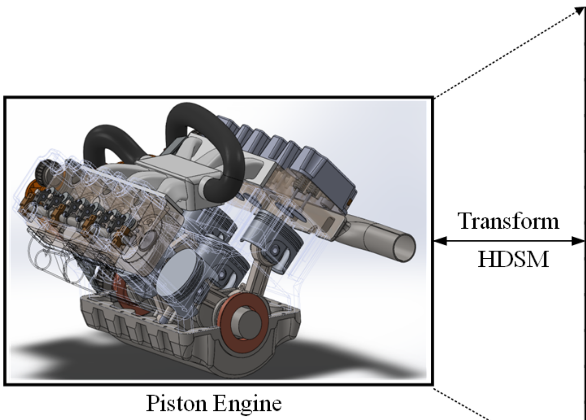


Fig. 5 Piston engine research and development requirements

4) Meanwhile, SysML can be used to intuitively and unambiguously describe the relationship between the stages of the development module and the development sequence, as shown in Fig.7.



		R_1	R_2	R_3	R_4	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8
Functional Req	R_1												
Performance Req	R_2	0											
Structure Req	R_3	0	0										
Dimension Req	R_4	1	0	0									
Body Design	A_1	1	1	1	1								
Crank link Mechanism	A_2	1	1	1	1	1							
Valve Mechanism	A_3	1	1	1	1								
Combustion supply system	A_4	1	1	1	1								
Lubrication system	A_5	1	1	1	1								
Cooling system	A_6	1	1	1	1								
Ignition system	A_7	1	1	1	1		1						
Starter system	A_8	1	1	1	1								

Fig. 6 Engine structure diagram

Table 3. Hierarchical Design Activity Matrix from Vehicle to Engine

	Vehicle System	Remote Control	Intell. Bearing	Infor. Bearing	Platform Chassis	Powertrain	Transmission	Power System	Crank Link	Body Design	Flywheel Design	Piston Selection	Ring Selection	Connecting Rod	Crank Design	Bearing Pad
Vehicle System																
Remote Control Vehicle	1															
Intelligent Bearing Platform	1															
Information Bearing Platform	1	1	1		1											
Platform Chassis	1		1	1												
Powertrain	1		1		1											
Transmission System	1		1		1	1		1								
Power System	1		1		1	1	1									
Crank Link Mechanism	1		1		1	1		1		1						
Body Design	1		1		1	1		1	1							
Flywheel Design	1		1		1	1		1	1							
Piston Selection	1		1		1	1		1	1				1			
Piston Ring Selection	1		1		1	1		1	1			1				
Connecting Rod Design	1		1		1	1		1	1						1	1
Crank Design	1		1		1	1		1	1					1		1
Bearing Pad Design	1		1		1	1		1	1					1	1	

Table 4. Design Activity Reachability Matrix

	Vehicle System	Remote Control	Intell. Bearing	Infor. Bearing	Platform Chassis	Powertrain	Transmission	Power System	Crank Link	Body Design	Flywheel Design	Piston Selection	Ring Selection	Connecting Rod	Crank Design	Bearing Pad
Vehicle System	1															
Remote Control Vehicle	1	1														
Intelligent Bearing Platform	1		1													
Information Bearing Platform	1	1	1	1	1											
Platform Chassis	1	1	1	1	1											
Powertrain	1	1	1	1	1	1										
Transmission System	1	1	1	1	1	1	1	1								
Power System	1	1	1	1	1	1	1	1								
Crank Link Mechanism	1	1	1	1	1	1	1	1	1	1						
Body Design	1	1	1	1	1	1	1	1	1	1						
Flywheel Design	1	1	1	1	1	1	1	1	1	1	1					
Piston Selection	1	1	1	1	1	1	1	1	1	1		1	1			
Piston Ring Selection	1	1	1	1	1	1	1	1	1	1		1	1			
Connecting Rod Design	1	1	1	1	1	1	1	1	1	1				1	1	1
Crank Design	1	1	1	1	1	1	1	1	1	1				1	1	1
Bearing Pad Design	1	1	1	1	1	1	1	1	1	1				1	1	1

Table 5. Hierarchical representation of the original matrix

	Vehicle System	Remote Control	Intell. Bearing	Infor. Bearing	Platform Chassis	Powertrain	Transmission	Power System	Crank Link	Body Design	Flywheel Design	Piston Selection	Ring Selection	Connecting Rod	Crank Design	Bearing Pad
Vehicle System																
Remote Control Vehicle	1															
Intelligent Bearing Platform	1															
Information Bearing Platform	1	1	1		1											
Platform Chassis	1		1	1												
Powertrain	1		1		1											
Transmission System	1		1		1	1		1								
Power System	1		1		1	1	1									
Crank Link Mechanism	1		1		1	1		1		1						
Body Design	1		1		1	1		1	1							
Flywheel Design	1		1		1	1		1	1							
Piston Selection	1		1		1	1		1	1				1			
Piston Ring Selection	1		1		1	1		1	1			1				
Connecting Rod Design	1		1		1	1		1	1						1	1
Crank Design	1		1		1	1		1	1					1		1
Bearing Pad Design	1		1		1	1		1	1					1	1	

After hierarchical clustering, from ground unmanned roadbed platform to engine research and development is divided into 7 research and development levels, as shown in Fig.7 (a), the first research and development level is composed of {ID1.1 Vehicle System} The second level consists of {ID2.1 remote control System, ID2.2 intelligent Bearing platform System}; the third level consists of {ID3.1 platform chassis system, ID3.2 Information Bearing Platform System}; the fourth level consists of {ID4.1 powertrain}; the fifth level consists of {ID5.1 transmission system, ID5.2 power system}; the sixth level consists of {ID6.1 Crank connecting rod mechanism, ID6.2 body design}; the 7th level consists of {ID7.1 flywheel design, ID7.2 piston selection, ID7.3 piston ring selection, ID7.4 connecting rod design, ID7.5 Crank design, ID7.6 bearing design} composition.

After the engine development hierarchy is obtained, the design module development process sequence of the product can also be obtained through the analysis of the directed graph, as shown in Fig.7 (b), which is development process of the rotary piston engine based on the activity diagram in SysML. The activity diagram clearly expresses the sequence of development module activities and lays the foundation for subsequent product design.

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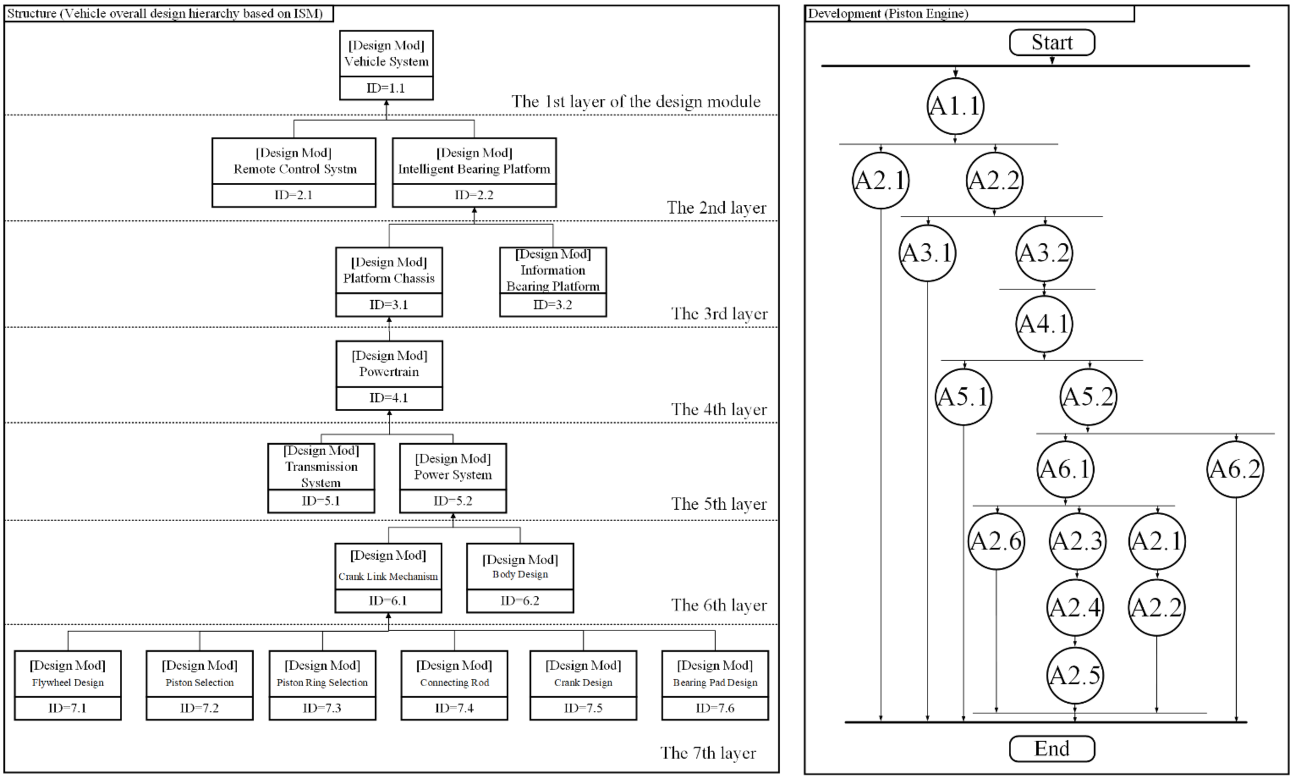

(a) Hierarchical design division from vehicle to engine based on SysML (b) SysML-based development activity flow chart

Fig. 7 SysML-based approach for vehicle-to-engine development

6. Conclusion

This paper firstly uses the combination of HDSM and SysML to model and optimize the complex product design and R&D process to obtain the preliminary division scheme, and then uses the directed graph, reachability matrix and strong connectivity judgment matrix to further plan the preliminary division scheme The design effectively reduces the types and coupling of complex product designs, improves the interoperability and utilization of complex product designs, and also improves the design efficiency of ground unmanned roadbed platforms. Finally, SysML graphical modeling is used to express the relationship of the developing process intuitively, and the series spectrum of complex product modularization is obtained as a guide to plan the functional modules of complex product design, avoiding unnecessary redundancy.

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