Modeling and Simulation of Top-level Design Based on MBSE

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Abstract. To solve the problem that it is difficult to evaluate and optimize the top-level system design scheme of complex products, a modeling and simulation method of top-level design based on MBSE is proposed. Through the use of SysML to describe the requirements of the system and the functional decomposition and interface of the subsystem, the system model is established; then, the mapping relationship between the SysML model and the Petri net is established, and the SysML model is transformed into the Petri net model. The model is verified by the Petri net simulation tool to evaluate the rationality of the requirements and the completeness of the overall indicators. The simulation results show that 100 optimization design variables and 10 optimization constraints can be achieved to meet the requirements.

1. Introduction

The traditional system engineering design method is a document driven design method. The design results in each stage are presented in the form of words, charts and other documents, and the information is also transmitted in the form of documents between each design stage. In the application, there are the following problems: 1) inadequate expression of design scheme, sometimes the document information can not fully express the designer's intention; 2) ambiguity of information expression, different designers may have different understandings for the same design scheme in the form of document; 3) complex system is a system involving many disciplines, and there are different modeling tools and modeling languages in different fields, which makes it difficult for designers to communicate with each other in a standardized and unified way; 4) the lack of formal definition of documents makes it difficult for designers to carry out effective simulation and validation of design schemes, and to find errors in design schemes in various stages; 5) it is very difficult to change. Because of the large number of documents, it will be very difficult to make sure that all the contents that need to be changed are changed. As a result, the redundancy of the scheme is large, the design efficiency of the system is low, and the adaptability of the design scheme to the requirement change is weak, which has become increasingly unable to meet the requirement.

The model has always been an important element for designers to study complex systems. Model-based system engineering (MBSE) is a model centered hierarchical design method of system engineering, which is a highly abstract and general step and method to deal with problems[1-4]. MBSE is driven by the model. It realizes the system design of the product through the continuous evolution and iteration of the model from the beginning of the requirement stage, and ensures the correctness and optimization of the design scheme at the system engineering level.

The top-level modeling is a modeling technology that abandons the concrete physical entity of the system, and represents the system only by function, behavior and structure. Common top-level
modeling methods include object-oriented modeling method, UML based modeling method, agent-based modeling method, Petri net based modeling method, multi-resolution modeling method and SysML based modeling method.

Based on the research and development of a complex equipment, MBSE is applied to the whole process of equipment scheme demonstration, design and research and development in this research. The top-level design modeling method based on SysML is used to build the system model, and then the established SysML model is transformed into Petri net model, which is verified by the corresponding simulation tools.

2. Top-level Design Modeling and Simulation

System modeling language (SysML) is developed on the basis of UML. It is a modeling language of system engineering method based on model. SysML has a friendly user interface, and the SysML model can be easily programmed and implemented. Using SysML modeling language for system modeling is not only convenient and intuitive, but also reusable to ensure the consistency of design process and reduce the ambiguity between models. SysML can support the detailed description, analysis, design, verification and validation of various complex systems in the way of graphical multi view modeling. The structure of SysML is shown in Fig.1. Nine diagram models of three classes (requirement diagram, structure diagram and behavior diagram) are defined to describe all aspects of system engineering.

![Fig.1 Structure of SysML](image)

![Fig.2 Modeling process](image)

Requirement diagram emphasizes the traceability between requirements and the satisfaction of design to requirements; structural diagram describes the static structure of the system, emphasizes the hierarchy of the system and the interconnection between objects; behavioral diagram describes the dynamic behavior structure of the system, the behavior of objects in the system, including their activities, interactions and state history.

The system top-level model based on SysML can describe the decomposition relationship from requirement to system, subsystem, component and implementation, and it is convenient to model the structure, behavior, requirement and attribute constraint relationship of complex products. Different diagrams are defined to describe different sides of the system, so as to realize the design process and information management based on the model.

The core of MBSE is to use the model to describe the design process of the system. The modeling method of the top-level system design model based on MBSE mainly includes the following three steps: 1) establish the system function from the user requirements; 2) establish the system structure from the system function; 3) detail the system behavior and feed it back to the top-level design in the detailing process, and finally determine the design of the whole system and establish the top-level model of the system through the hierarchical design[5-7]. Fig.2 is the modeling process.
2.1 Requirement Analysis

The requirement for the system is the starting point of the whole system design. Once the requirement changes, it usually needs to redefine the whole system design scheme. Requirements include not only user requirements, but also technical requirements, maintenance requirements and recycling requirements. Therefore, it is necessary to carry out requirement analysis to transform the user's requirements into the requirements for system design.

The premise of system design is to understand the requirements of users, including understanding the requirements of system users and potential users, the environment of the system, etc. The main output results of requirement analysis are requirement diagram, use case diagram, user requirements and system functional requirements. The requirement diagram describes all the functional expectations of system users, and summarizes the requirements in the form of hierarchy and classification.

As shown in Fig.3, the requirements analysis can be divided into three phases. First, the requirement analysis task flow starts from the analysis and improvement of user requirements, and generates system requirements and associated user requirements to system requirements. Second, transform these requirements into the functional requirements required by the system. Thirdly, the use cases of the system are defined according to the system requirement specification. Use case describes the system from a specific operational aspect, which describes the behavior of roles (users) and the information flow between roles and use cases in detail. Use cases describe how potential users use the functions of the system without involving the internal structure of the system[8-9].

Fig.3 Workflow of requirements analysis
2.2 System Function Analysis
System function analysis is the analysis of system behavior and the relationship between system and external environment when the internal structure of system is unknown. The analysis of system function mainly involves the activity interaction behavior between system and external system and the accompanying information interaction behavior.

Establishing the function of the system is the first and most critical step in the process of top-level design of the system. The purpose is to determine the function and boundary of the system from the requirement. The function of the system is a collection of functional requirements and constraints to meet the requirements of users. The system functions are divided into general functions and sub functions. Among them, the total function corresponds to the input-output relationship of the top-level design of the system, and the change of the total function of the system will cause a huge change in the structure and behavior of the whole system, so at the beginning of the system design, the function and boundary of the system should be clear. The total function of the system can be decomposed into several sub functions with lower complexity until the function elements cannot be decomposed.

SysML provides requirement diagram and use case diagram to describe use cases, actors and their interrelations, which can describe system functions from the perspective of users. In the early stage of requirement analysis and function establishment, use case diagram can quickly identify the external system and users interacting with the system, and describe the behavior at the highest level. The package diagram in SysML can be used to further decompose the functions of the system, describe the functions of each subsystem of the system, represent one subsystem of the system with one package, and manage the model more conveniently.

System function analysis is based on the analysis of functional requirements to transform requirements into its consistent system functions. The output of the requirements phase is a use cases described from the user's perspective. In the functional analysis phase, each use case is materialized and transformed into an executable model. The executable model is described by the behavior description diagram of SysML, such as activity diagram, state machine diagram and sequence diagram.

2.3 System Synthesis
System synthesis phase focuses on decomposing the physical architecture and understanding the internal structure of the system. This stage of analysis is called system structure white box analysis. System function analysis describes the activities, information interaction and interface relationship between the system and the external environment from the overall level. Based on the function analysis, the system synthesis further analyzes the internal structure of the system, the interaction behavior between the constituent subsystems and the information interaction interface.

The synthesis stage consists of three parts: architecture analysis, architecture design and detailed architecture design. Fig.4 shows the workflow of system synthesis. The synthesis phase focuses on the development of a physical architecture capable of performing the required functions within specified performance limits[10-11].

System functional analysis defines what a system should do, rather than how it should perform its functions. The purpose of architecture research in the architecture analysis phase is to determine the best way to achieve specific functional capabilities in a reasonable way. That is to determine how to realize the system functions.

Based on the optimal design concept in architecture analysis research, architecture design decomposes the selected system block into several parts, and describes the system structure determined by architecture analysis in SysML block definition diagram and internal block diagram.

The detailed architecture design phase focuses on the definition of ports and interfaces, as well as the definition of the lowest level system block state behavior of the architecture decomposition.

The correctness and integrity of the system architecture model is verified by model execution. When the model function is verified, the architecture design can be analyzed according to the performance and security requirements.
2.4 Simulation and analysis of model

The iterative development process of system structure design is a process that can constantly find and correct model errors, which can be divided into improper use of model graphics, missing model elements and model logic errors.

Since the model established by SysML is static, there is no effective validation method and the hierarchical coupling relationship of the model cannot be handled. As a modeling tool, Petri net has both intuitive graph representation and rigorous mathematical analysis method, which can not only describe the static characteristics of the system, but also describe the dynamic characteristics of the system, especially suitable for describing complex systems with concurrent, asynchronous and distributed characteristics. Therefore, integrated application of Petri net and SysML in the model analysis and simulation phase can help to find out the errors of the model as early as possible by converting the SysML model into a Petri net model and simulating the model with Petri net simulation tools, avoiding the high risk caused by testing after the end of system development and design. By executing the transformed model and debugging the built model, the system can be visually analyzed and the model logic accuracy verified during the model construction process, which greatly reduces the complexity of subsequent system design and provides correct guidance for the whole life cycle of system modeling.

3. Test Results and Discussions

The top-level design modeling and simulation method based on MBSE was applied to the design of a complex equipment. The modeling process included three stages. Firstly, SysML was used to model the system, then the model was transformed into a Petri net model. Finally, the transformed Petri net model was analyzed and simulated.

The modeling of SysML model is based on the IBM Rational Rhapsody platform, and the transformation of SysML to Petri net is based on the interface provided by IBM Rational Rhapsody platform. Self-developed plug-in modules are developed to realize the function expansion of Rhapsody. The top-level design tool of the system realizes the modeling, verification, simulation and
analysis of Petri net model by developing self-developed software platform. Fig.5 is the SysML model structure file, and Fig.6 is the SysML-Petri net transformation system. Fig.7 is the diagram of the Petri net model simulation and analysis system.

![SysML model structure file](image1)

![SysML-Petri net transformation system](image2)

![Petri net model simulation and analysis system](image3)
The simulation results show that through the continuous evolution and iteration of the model, 100 optimization design variables and 10 optimization constraints can be achieved to meet the requirements of users.

4. Conclusion
In this study, the idea of top-level design based on MBSE is applied to the overall scheme demonstration and design process of complex equipment. The research on MBSE based top-level design modeling and simulation technology is carried out. SysML modeling language is used to model the system at the top level, and then the model is transformed into Petri net model. Finally, the transformed model is analyzed and simulated in Petri net model analysis and simulation system. Good results have been achieved.

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