



Discussion on Application of Model-Based Systems Engineering Method to Human Spaceflight Mission

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Abstract. Considering the fact that design data exist in different documents dispersedly and are difficult to keep consistent and hard to trace, the concept of MBSE (model—based systems engineering) method is introduced. Firstly MBSE method can graphically support system requirements, design, analysis, verification and validation activities in whole life cycle. Then a general process of MBSE method is summarized, creating a requirement model to guide the construction of functional model and physical architecture model etc. Based on a set of predefined rule the relations among models are set up, by which relevance among design elements and information can be analyzed and searched out. In the end, an example is presented to show how to apply MBSE method to design manned spacecraft docking missions. It is concluded that MBSE method can improve the communication, increase work efficiency, and reduce design risk. The work is a good reference for further application.

Keywords: Systems engineering · Human spaceflight · MBSE · Requirement model · Functional model · Physical architecture model

1 Introduction

Manned space engineering is a complex system engineering process, which has the characteristics of large scale, high technology level, high reliability and safety requirements, long development cycle, many participants and huge investment. In the development process, from the overall development requirements of the project to the product realization and on orbit operation, a large amount of design information with complex relationship will be generated, such as system, subsystem, stand-alone design requirements and interface definition. At present, the information is mainly stored and managed in the form of documents. With the task becoming more and more complex, the scale of the system expanding, the subjects involved increasing, and the inconsistent state of system parameters in different documents often occurs, which leads to many security risks. Therefore, a new method and means are urgently needed to change this situation [1].

With the development of computer and information technology, it is more and more easier to use object-oriented, graphical and visual system modeling language to describe the system, and the application proportion of model in system design is also increasing. A method called “model-based system engineering” (MBSE) arises at the

historic moment. In MBSE method, the system requirements, function model and physical architecture model in a graphical and structured way. These models are used as the main way to describe the components of the system and control its evolution process, so as to realize the design and management process of system engineering project. MBSE method can effectively solve the problems of document based method in parameter acquisition and technical status management, and has been applied in the fields of aviation, aerospace, ship and so on. Through decades of development, China has accumulated rich engineering experience in system engineering, but the research on MBSE method is still in its infancy, only in the system modeling language and the development of some small systems. In order to solve this problem, this paper first studies the development of MBSE method, analyzes its advantages, puts forward the general workflow, and then gives an application example of manned spacecraft rendezvous and docking mission design by using this method, explores the transformation from traditional system engineering method to MBSE method, which can provide a reference for the application of MBSE method in manned space mission of our country.

2 Overview of MBSE Method

2.1 The Concept and Advantage of MBSE

The international Association of System Engineering (INCOSE) gave the definition of MBSE method in 《Vision 2020 of system engineering》 published in 2007: MBSE method is the application of formalization and standardization of modeling method in system engineering activities, so that the modeling method can support system requirements, design, analysis, verification and validation activities. These activities start from the conceptual design stage [1]. From the definition, it can be seen that there is no essential difference between MBSE method and traditional document based system engineering method in terms of basic theory and basic process. The difference is mainly in the management mode of design process, work form and display form of design results.

In the document based system engineering method, a few graphics are used to visualize the content that is difficult to describe by text, which is easy for people to understand. At this time, the graphics are only used to assist the text to complete the description of the system. With the development of computer technology, graphic modeling becomes easier, and the proportion of graphic model in the process of system engineering is also increasing, which gradually develops into MBSE method. MBSE method takes the model as the basis of system description, and realizes the whole process from conceptual design, scheme design, and experimental verification to engineering implementation with visualized model [2].

- (1) Improve the efficiency of understanding and communication. The first mock exam is more acceptable than the text, and the graphical symbols are written in character. It is intuitive and image, and ensure the integrity of information. It makes the understanding of the same model easier for different personnel to reach agreement, and improves the communication efficiency among different designers.

- (2) Data acquisition is easy. The minimum object of document based system engineering method is document. The information users need is scattered in a large number of documents, so it takes a huge amount of work to find. The minimum object of MBSE method is data. Combined with database management method, users can directly obtain the required index parameters, which can greatly reduce the workload of designers.
- (3) Good traceability of technical status. MBSE method will continue to establish the relationship between the models in the process of work, through these relationships to achieve the traceability and correlation analysis of the technical status, and complete the comprehensive analysis and control of the technical status.
- (4) Integration of design and verification. MBSE emphasizes that design and verification should be considered at the same time in the process of work. By establishing the relationship between verification model and requirement model, function model, and other relevant models used in the design process, the verification coverage analysis is carried out to ensure that all projects meet the verification requirements.

2.2 Typical MBSE Method and Related Tools

Some well-known companies and research institution have gradually formed a method suitable for their own development process through continuous accumulation in the process of using MBSE method for product development. The typical methods are shown in Table 1 [3].

Table 1. Typical MBSE methods

Serial number	Method Name	Organization or Company
1	Harmony system engineering method	IBM Corporation
2	Object oriented system engineering method	INCOSE
3	Unified development process	Rational Corporation
4	Vitech model based system engineering approach	Vitech Corporation
5	State analysis method	Jet Propulsion Laboratory (JPL)
6	Object process method	—

In the early development of MBSE method, system engineers mostly used behavior diagram, function modeling in integrated computer aided manufacturing (IDEF) and other methods to carry out their work [4], but the symbols and semantics used by these methods are different, resulting in information reuse between them. The lack of a unified modeling language and tools severely limits the development of this method.

Unified Modeling Language (UML) is an object-oriented standard modeling language. Since it was approved as a standard by object management group (OMG) in 1997, it has made remarkable achievements in software system design, mechanical

design, enterprise business process design, data processing system design and other industries. However, the original UML was proposed to support the development of software system, and the models it provided focused more on the software development process, which had some defects in the process of supporting MBSE method. In order to transform UML into a language suitable for system engineering, a system modeling language (SysML) cooperative organization has defined a system modeling language SysML based on UML 2.0, which is specially extended to support MBSE method [5].

Based on UML and SysML, a variety of MBSE software are developed. At present, there are three kinds of MBSE software: One only supports requirement management, and the other only supports system modeling. The whole system engineering process can be completed only when they are used together; because there are some compatibility problems when they are used together, the third kind of software appears, which integrates the functions of requirement management and system modeling into the same environment.

Table 2 lists several commonly used softwares, among which the corresponding software of serial numbers 1 and 2 only support requirement management, while the corresponding softwares of serial number 3, 4 and 5 only support system modeling, and they should be used together; the corresponding software of serial number 6 is an integrated development environment, under which users can carry out requirements management and system modeling.

Table 2. MBSE tools

Serial number	Software name	Organization or company
1	RequisitePro requirement management tool	Rational
2	DOORS requirements management tool	Telelogic
3	Rational Rose system modeling tool	Rational
4	Telelogic Tau system modeling tool	Telelogic
5	Rhapsody model driven development tool	IBM
6	Cradle system engineering integrated environment	3SL

3 Process of MBSE Method

MBSE method covers the design and management from largescale system, to sub-system and component level. Its basic process is the same as the traditional system engineering method, which starts from the analysis of task requirements are transformed into system function, and various “activities” required by the system to complete the task are defined. Finally, the results of functional analysis are mapped to the equipment and components one by one [6].

The ultimate goal of MBSE method is to build a complete tested and verified system architecture based on the model. In the whole design process, the most basic is

to build the system requirement model, function model and physical architecture model [7, 8].

(1) Construction of demand model

Requirement model refers to the set of requirements from the top to the bottom of the system, as well as the logical relationship between them. According to different emphasis, the requirements can be divided into functional requirements, performance requirements, interface requirements, reliability requirements, security requirements, human factors engineering requirements, etc. The requirement model is used to transform the unclear expectations of various stakeholders. These top-level requirements are divided into functional requirements and performance requirements, and are decomposed and allocated in the system. From the system to the subsystem and then to the stand-alone components, this decomposition and allocation process continues until the complete design meeting the requirements is completed. The construction process of requirement model 1 is shown in Fig. 1 [7, 9].

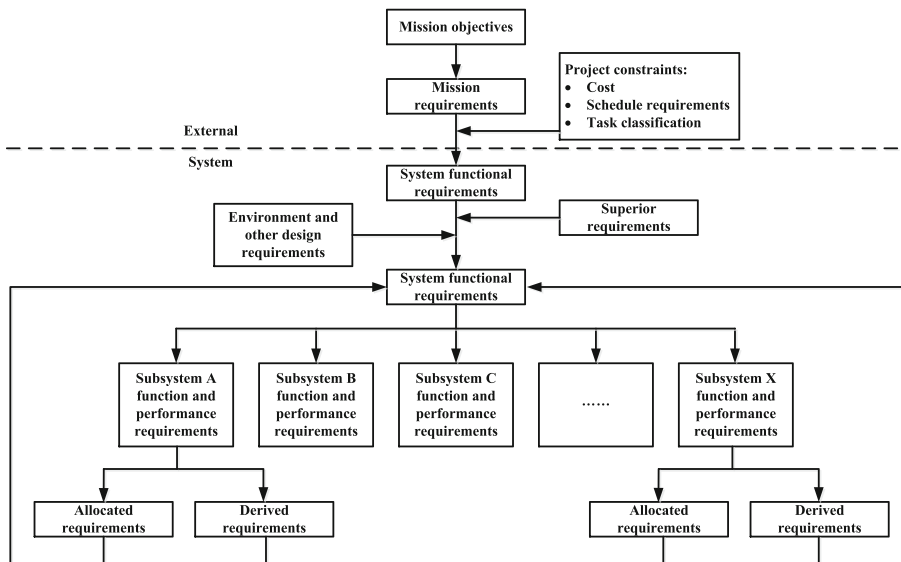


Fig. 1. Construction of requirements model

(2) Function model construction

Function model refers to the set of all functions required by the system to complete the given mission objectives, including the functions corresponding to the system level (such as manned spacecraft), subsystem level (such as measurement and control system), product level (such as sensors), and even smaller units, and the logical relationship between them, which is used to guide the design of system composition. Based on the requirement model, the function model analyzes the system function through logical decomposition. At the same time, based on the

analysis of the mission process, it combs the flight events in the whole process, and then identifies the system function of each level through the flight events, as shown in Fig. 2. After that, the functions are summarized step by step to form the functional module division of the system. In addition, in the process of building functional model, the summarized functions should be matched with the items in the requirement model to ensure that each requirement has corresponding function. For the requirements that are not covered, we should consider whether they are reasonable and whether we need to add corresponding functions to support them. For functions that do not support system requirements, consider deleting them.

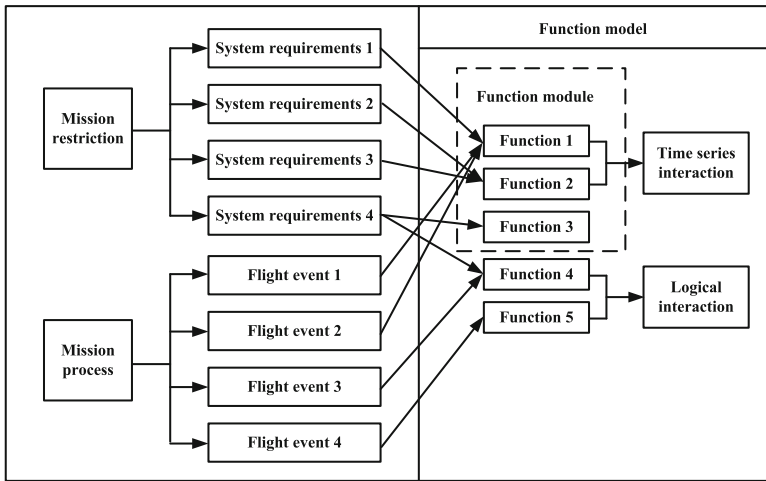
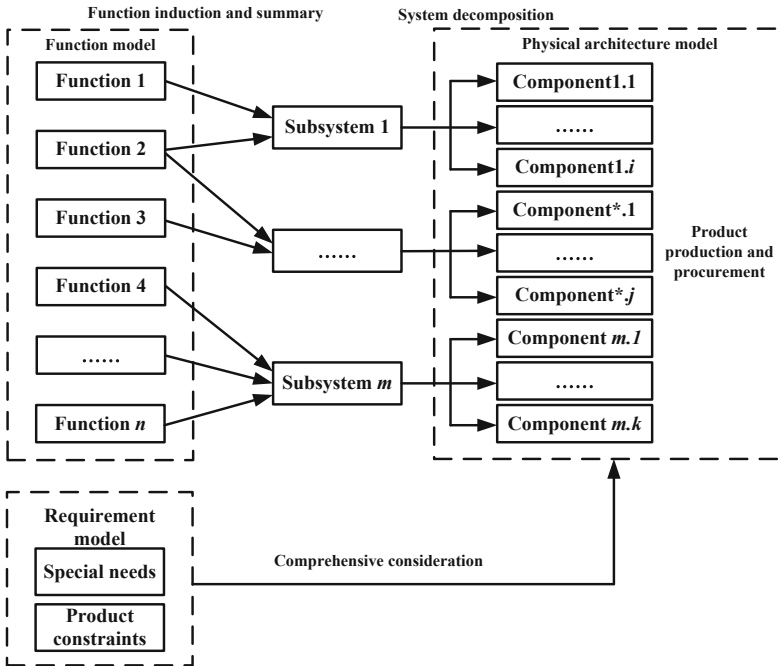


Fig. 2. Construction of functional model

- (3) The physical architecture model is used to describe all the elements of the system and the interface relationship between them. It is also composed of the hierarchical structure from the system level to the product, or even smaller units. When building the physical architecture model of the system, based on the demand model and function model, we comprehensively consider the performance index, system efficiency, development cost, system interface, technical risk, etc., carry out multi scheme that can meet the user’s needs and better complete the system function. The construction process of physical architecture model is shown in Fig. 3.

In addition to the above three basic models, the system interface model, product structure model, risk analysis and verification model are also needed to complete the whole task design [10]. After building the model for task design, the relationship between different models should be established according to the logic rules made in advance, so as to achieve the comprehensive accessibility of the data in the whole project. The whole process is iterated and refined until the whole design, verification



Note: n and m are the number of functions and subsystems respectively, i, j, k are the number of components.

Fig. 3. Construction of physical architecture model

and working process can be clearly described. Finally, a complete, consistent and convenient traceability and query system is established to realize parameter query, coverage analysis and other work, so as to ensure the integration of system design model, avoid design conflicts between various components and reduce risks.

4 Application of MBSE Method in the Mission Design of Manned Spacecraft

This section studies the general process of requirement analysis and system design for manned spacecraft rendezvous and docking mission, including requirement analysis, flight event analysis, function analysis, product structure model creation, and model relationship establishment.

(1) Requirement analysis model

In the analysis of manned spacecraft rendezvous and docking mission requirements, from the measurement and control system, astronaut system and the requirement of the target aircraft for manned spacecraft, a preliminary analysis is carried out. The requirements of manned spacecraft are transformed into the definition of the problem, and they are transformed into a set of statements expressed as “how to complete”. Analyze the requirement of manned spacecraft when

completing rendezvous and docking mission, and the specific situation is shown in Fig. 4.

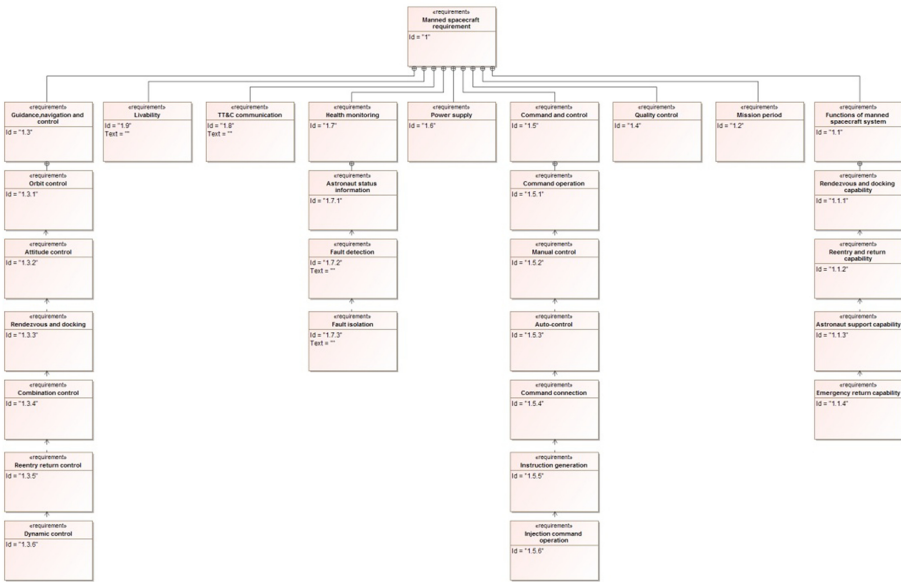


Fig. 4. Requirement model

(2) Flight event analysis model

Flight event analysis is used to convert the high-level requirements in the process of requirement analysis into specific events. Through detailed analysis to ensure the rationality of these events, a preliminary flight plan is obtained, which lays the foundation for functional analysis. When analyzing the flight events of rendezvous and docking of manned spacecraft, it is necessary to comprehensively consider the user's needs, divide the mission process, analyze the stages of completing the mission, and then subdivide each stage to analyze the flight events of the whole process, so as to prepare for the next functional analysis, as shown in Fig. 5. The nodes led out by and in the figure indicate that each event is parallel.

(3) Functional analysis model

Based on the results of flight event analysis, the functional requirement of rendezvous and docking mission for manned spacecraft can be sorted out. In the process of functional analysis, the corresponding functional requirements should be given according to the needs of users. Function model and requirement model feedback information to each other and refine iteratively. The function model obtained from the analysis can further guide the system composition analysis and

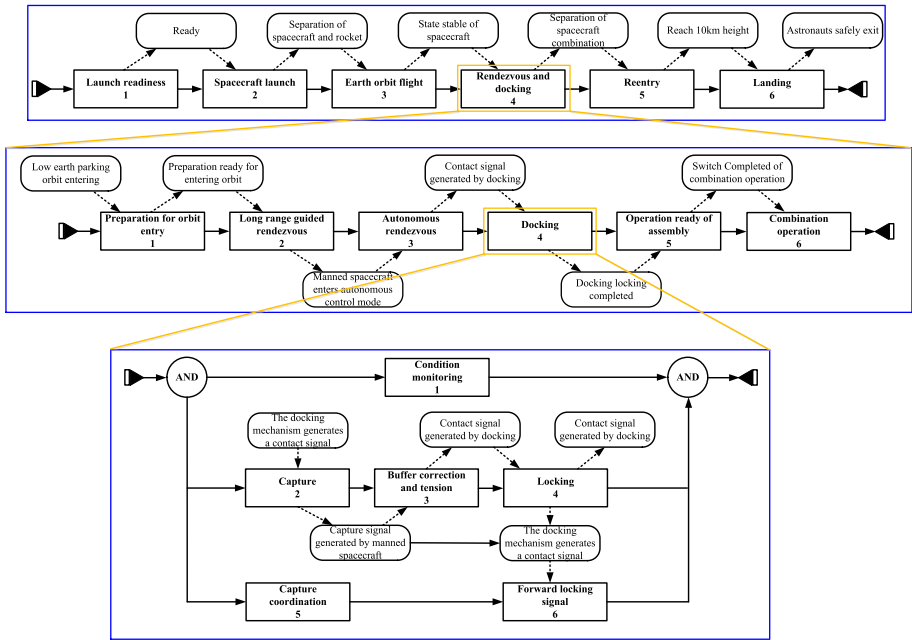


Fig. 5. Flight events analysis

other work. The preliminary results of functional analysis of rendezvous and docking manned spacecraft are shown in Fig. 6.

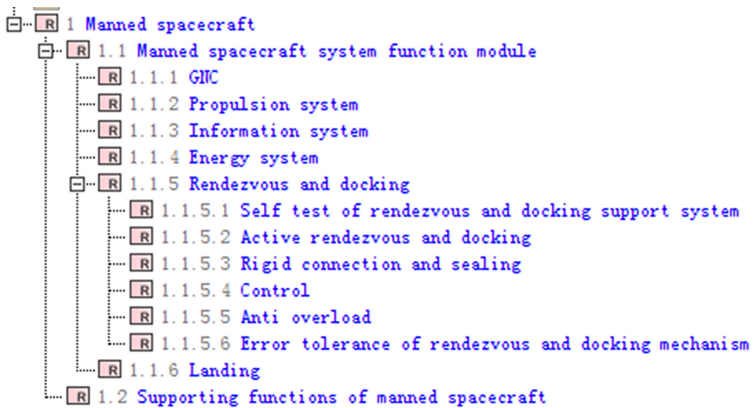


Fig. 6. Function model

(4) Product structure model

Product structure model is the bridge between the design and the real object. The product in the product structure model can be a mature application of existing products (such as the return cabin seat), can also be component (such as the seat lifting device). The product structure model of some manned spacecrafts is shown in Fig. 7.

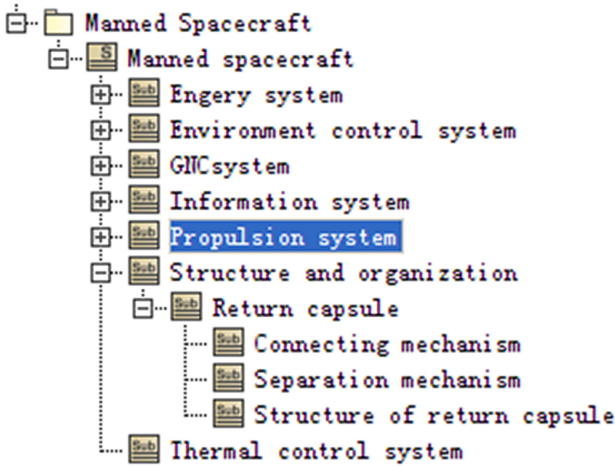


Fig. 7. Product structure model

(5) Each model in MBSE

Each model in MBSE has corresponding logical relations, through which we can use the upper level model to guide the construction of the next level model. The parameters of different models are associated to realize the analysis of the model and the relationship between model parameters. In the whole design process, the tracking of design elements, requirement coverage analysis and simulation verification completeness analysis are realized. The logical relationship between models is mainly composed of relationship orientation and relationship content, as shown in Fig. 8. The content of requirement model is satisfied by function model, and the content of function model is allocated to physical architecture model, which is realized by physical architecture model. Each model itself should be decomposed and refined, and its relationship can be decomposed or related.

In the process of using MBSE method to design the system, designers can design in a unified database, and the parameters in the database can be updated in real time with the modification. Therefore, designers can concentrate on the system design instead of searching for parameters in a large number of documents, which not only improves the work efficiency, but also avoids the errors caused by the untimely update of documents.

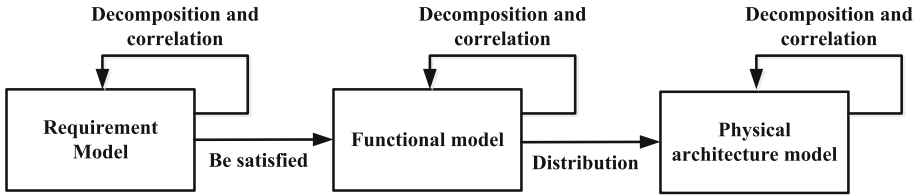


Fig. 8. Relations among primary models

Table 3 shows the statistical results of requirements by using data query, which can easily control the design status and progress. In addition, through the management of the unified database, more data mining and utilization can be realized.

Table 3. Statistic results of requirements

Query name	Number		
All requirements	106		
All requirements	Item status		
	Accepted	11	10.4%
	Adopted	8	7.5%
	Alternative	9	8.5%
	Solidified	0	0%
	Controversial	2	1.9%
	Rejected	3	2.8%
	Under advisement	3	2.8%
	Passed the examination	0	0%
	Suspicious	0	0%
	Pending	0	0%
	Unprocessed	70	66%
	Other	0	0%

5 Conclusion

MBSE method can cover the whole process from conceptual design, system design, and experimental verification to engineering implementation, and describe the system more intuitively. It can easily realize the deterministic and standardized management of system information interface, realize the traceability and coverage analysis of engineering elements such as requirements, design and verification, and ensure the effective control of technical state. In this paper, the MBSE method is applied to rendezvous and docking mission of manned spacecraft and how to use this method to carry out mission design is preliminarily demonstrated. At present, China has accumulated some experience in the system engineering method, but compared with foreign countries, there is still a certain gap in the design standards, top-level specifications and design tools of MBSE method. In the follow-up accumulation and development, China should keep up

with the development trend of system engineering method system, further study MBSE method, combined with the mission requirements of China's major aerospace engineering projects, put forward the MBSE method workflow suitable for aerospace, in order to promote the development and application of MBSE method in aerospace field.

References

1. Kunsheng, W., Jianhua, Y.: Research and practice of model-based systems engineering. *Aerospace China* **11**, 52–57 (2012)
2. Sun, Y., Ma, L.: Model-based systems engineering and systems modeling language. *Comput. Knowl. Technol.* **7**(31), 7780–7783 (2011)
3. Estefan, J.A.: Survey of model-based systems engineering (MBSE) methodologies. INCOSE, San Diego, CA (2008)
4. Ramos, A., Ferreira, J., Barcelo, J.: Model-based systems engineering: an emerging approach for modern systems. *IEEE Trans. Syst. Man Cybern.* **42**(1), 101–111 (2012)
5. Caiyun, J., Weiping, W., Li, Q.: SysML: a new systems modeling language. *J. Syst. Simul.* **18**(6), 1483–1492 (2006)
6. Baozhu, G.: What is systems engineering. *Spacecraft Eng.* **22**(4), 1–6 (2013)
7. Zhu, Y., Li, Q., Yang, F., et al.: *NASA Systems Engineering Handbook*. Electronic Industry Press, Beijing (2012). NASA. translated
8. Fuchs, J.: *Multi-Disciplinary MBSE Approach in Industrial phases*, AIAA 2012–2532. AIAA, Washington D.C. (2012)
9. Russell, M.: Using MBSE to enhance system design decision making. *Procedia Comput. Sci.* **8**, 188–193 (2012)
10. Tepper, N.A.: Exploring the use of model-based systems engineering (MBSE) to develop systems architectures in naval ship design, ADA541194. Massachusetts Institute of Technology, Cambridge (2010)