Journal of Systems Engineering and Electronics
Vol. 37, No. 3, June 2026, pp.904 – 920

Integrated modeling for civil aircraft PHM and maintenance support based on DoDAF and MBSE

CHEN Jie, ZHANG Gaofei*, GAO Ke, LV Bijiang, LI Chen, and SUN Chang

School of Civil Aviation, Northwestern Polytechnical University, Xi'an 710072, China

Abstract: Integrating prognostics and health management (PHM) with the existing maintenance support system of systems plays an important role in implementing reliability-centered maintenance (RCM). However, the increasing complexity and integration of civil aircraft systems pose challenges for conventional document-based systems engineering (DBSE) practice. Aiming at the specific problems of poor modeling degree, weak traceability between problem and solution domains, and insufficient integration in civil aircraft PHM development, a model-based systems engineering (MBSE) approach is adopted to overcome the limitations of DBSE method. This paper proposes a structured integrated modeling method to facilitate PHM functional integration with other aircraft systems. An MBSE modeling method based on traceable requirements, functional, logical, and physical models, is applied in the integration process. Additionally, a multi-viewpoint analysis method within the Department of Defense Architecture Framework (DoDAF) is introduced to illustrate the modeling elements and processes from a multi-dimensional perspective. The modeling logic and architecture are subsequently presented, followed by examples of requirements, functional flows, and resource flows models using the systems modeling language (SysML). Finally, a preliminary logic simulation verification is conducted as a case study of typical PHM functional integration with maintenance support. The case study results demonstrate that the proposed method enhances information traceability and consistency, which can offer theoretical support and technical reference for the development of maintenance support system.

Keywords: Department of Defense Architecture Framework (DoDAF), model-based systems engineering (MBSE), prognostics and health management (PHM), maintenance support.

DOI: 10.23919/JSEE.2026.000116

1. Introduction

Prognostics and health management (PHM) is a crucial technology for enhancing the safety and reliability of complex systems, widely applied in the aerospace and defense industries [1–5]. While retrofitting PHM capabilities into existing aircraft systems presents implementation limitations, functional integration may offer a potential solution for achieving some level of PHM [6]. The overall integration of PHM represents a complex systems engineering (SE) practice, involving interactions between various system of systems (SoS), such as operational support, customer service, and maintenance support. A robust SE approach can facilitate efficient functional integration of PHM with maintenance support, attributed to its generalized logical framework and greater focus on the goals to be achieved. Recently, scholars have recognized the importance of integrating PHM information and conducted exploratory studies on the structure, capability, and behavior of civil aircraft maintenance support based on PHM [7–10]. However, overall integration methodologies for PHM remain limited [11–13], and there is a need to focus more on the efficient integration of hybrid PHM applications [14,15].

As civil aircraft maintenance support trends toward scientific maintenance and logistics based on diagnostics and prognostics information [16], conventional maintenance methods are gradually being phased out [7]. PHM technology can significantly enhance maintenance efficiency and influence maintenance support resources and decision making [17,18]. Integrating PHM with the existing maintenance support SoS plays an important role in implementing reliability-centered maintenance (RCM), thereby reducing support costs and enhancing safety and reliability [7–9]. However, the increasing complexity and integration of civil aircraft systems pose challenges for conventional document-based systems engineering (DBSE) method, particularly in maintaining information consistency and traceability throughout the lifecycle [19]. Model-based systems engineering (MBSE) has emerged

Manuscript received July 15, 2024.
*Corresponding author.
This work was supported by the National Natural Science Foundation of China (52372433) and the Key Research and Development Projects of Shaanxi Province (2024QYZGJHX-01).

as a promising and powerful approach that uses models to support requirements analysis, function definition, architecture design, and other activities [20,21]. The department of Defense Architecture Framework (DoDAF) serves as the synthesized framework and conceptual model [22], ensuring standardized development, description, and integration of system architectures [23]. The visual accessibility of DoDAF viewpoints facilitates effective participation and communication among stakeholders (e.g., implementers, developers, and customers), enhancing the traceability of models, architectures, and viewpoints [24,25]. Therefore, we propose an integrated modeling method based on DoDAF and MBSE to enhance the integration of civil aircraft PHM with maintenance support from five different perspectives of mission, operation, function, logic, and physics [26,27].

To bridge the gap between the potential of PHM functional integration and its practical implementation, a structured integrated modeling method is presented. The main contributions of this study are summarized as follows:

(i) An MBSE modeling method is introduced based on traceable requirements, functional, logical, and physical (RFLP) models to support the PHM integration process. This model-based integrated method defines the process from the perspectives of vision, capability, operation, resource flow, and systems interface.

(ii) The RFLP integrated modeling process is realized to design a maintenance support system based on PHM in an iterative manner. This applied modeling process, based on a multi-viewpoint analysis method within DoDAF, enables a multi-dimensional and clear description of integrated elements and logic.

(iii) Engineering information is transmitted through system models described in system modeling language (SysML) instead of natural language, enhancing consistency and traceability between design and requirement domains. The case results demonstrate that a model-based integrated method applying DoDAF viewpoints can effectively fulfill the design requirements of complex aircraft systems.

The remainder of this paper is structured as follows: Section 2 reviews the relevant literature; Section 3 describes the proposed model-based integrated method based on DoDAF; Section 4 presents a case study on maintenance support based on PHM and the results of logical simulation; and Section 5 concludes the paper.

2. Literature review

2.1 Civil aircraft PHM and maintenance support

The Industry 4.0 paradigm is boosting the relevance of predictive maintenance [28], which utilizes condition monitoring information to detect anomalies, identify and diagnose occurring abnormal states, predict future evolution of degradation to failure, and estimate the remaining useful life [29–32]. In recent years, PHM research efforts have focused on algorithms, models, and methods for tracking the health state of monitored operating systems [32,33]. However, with increasing integration and complexity, PHM is no longer an isolated auxiliary for maintenance support [30], but has become an integral system that interacts closely with almost all other functional systems and subsystems [34]. Indeed, the PHM value chain extends further, with its information potentially influencing logistics and maintenance driven by PHM outcomes [35]. As discussed by Mohammadreza et al. [36], the next generation of intelligent maintenance systems needs to focus on developing an integrated PHM system. Guillen et al. [37] reviewed the role of PHM in maintenance systems and analyze how PHM techniques and methods can be integrated into RCM. Rath et al. [38] also emphasized that predictive maintenance is pivotal within Industry 4.0 and significantly impacts the successful implementation of RCM.

Recently, substantial research efforts in PHM technology have enabled civil aircraft health management and preventive maintenance at both component and system levels [39]. Conversely, only a few methods incorporate PHM information into maintenance and operational processes to support maintenance management, with some presenting only preliminary concept [30,40]. Guillen et al. [37] pointed out that advanced maintenance systems design has not been adequately studied after considering the potential of PHM solutions. Alaswad et al. [41] stated that maintenance decisions based on PHM information play an important role in the effectiveness of any industrial system's operation. Liu et al. [7] developed a civil aircraft PHM maintenance support system model in the system tool kit, which presents only part of the static structure and dynamic behavior without considering requirements analysis. In another effort, Chen et al. [42] adopted a service-oriented architecture to build an equipment maintenance support information system focused on sharing maintenance information and knowledge, but do not integrate PHM information.

Most PHM research has concentrated on maintenance strategies, ranging from reactive to preventive and condition-based maintenance [39,40,43]. However, most of these studies lack integration with traditional civil aircraft maintenance tasks, leading to difficulties in applying PHM to maintenance support [44]. It should be emphasized here that a preventive maintenance strategy can help minimize random failures but may also increase the consumption of spare parts and materials [39]. Therefore, it is essential to synchronize maintenance strategies and inventory management policies [45].

To bridge the gap between PHM information and maintenance support, this paper introduces the concept of a maintenance support system based on PHM. On the basis of traditional civil aircraft maintenance tasks and PHM potential, developing such a system is part of the complex systems integration process from a systems engineering view. As a result, several key elements should be considered. Among these elements are multi-level requirement analysis and decomposition, multi-viewpoint capability decomposition and allocation, and multi-dimensional structured model description [19]. A systematic approach is crucial for the effective management of the integration process [46]. Thus, a structured system engineering approach from multiple perspectives is recommended to support effective development of the maintenance support system based on PHM.

2.2 MBSE and DoDAF for complex systems modeling

To achieve full deployment of condition-based and predictive maintenance in practice, it is essential to integrate PHM information within maintenance and operational loops to maximize PHM potential [29,30]. However, implementation is in fact complex and, to effectively manage this complexity, SE approaches can provide valuable insights into how PHM interacts with maintenance support activities. As interactions and complexity between elements in engineered systems continue to increase, the SE community has turned to MBSE to manage complexity, maintain consistency, and ensure traceability [47,48].

The International Council on Systems Engineering (INCOSE) defines MBSE as a formal application of modeling to support requirements definition, design, analysis, verification, and validation [49]. As described in "Systems Engineering Vision 2035", SE will largely be model-based, utilizing integrated descriptive and analytical digital representations of the systems [50]. Wang et al. [51] outlined that MBSE elevates complex product development to a modern, digital, and systematic level. McMillan et al. [52] stated that MBSE is proliferating in the aerospace industry as a method for managing the development of complex cyber-physical systems. Hu et al. [30] also explained that MBSE has become a promising and powerful method for addressing the issue of "unclear requirements". Li et al. [26] investigated issues of complex systems integration in aircraft assembly and proposed a structured approach to support functional integration using RFLP models.

The RFLP approach provides an opportunity for systems engineering activities, including requirements management, functional analysis, logical architecture definition, and physical design, to better understand each other through traceable information [53,54]. These activities can be effectively linked to aircraft system development process, following a classical SE "V" model based on ARP4754B "Guidelines for Development of Civil Aircraft and Systems" [55,56]. It is important to note that the RFLP approach takes explicit system requirements as input but does not consider the process of identifying stakeholders and capturing their needs, goals, and objectives. Stakeholder engagement and information reusability (e.g., knowledge, architecture, and models) are becoming critical aspects of MBSE [57]. Borky et al. [58] emphasized that a major payoff from systematic application of MBSE results from cost and schedule savings achieved through architecture frameworks, which enable design reuse and commonality.

Architecture frameworks are very known in enterprise architecture (EA) development and SoS engineering (SoSE) [59]. DoDAF is identified to be more suitable for the SoS or EA modeling, while MagicGrid or HarmonySE is utilized as the system architecture modeling method [60]. The DoDAF viewpoints and models facilitate collaboration with various stakeholders in transforming needs into verifiable requirements and designing architectures that define the functional, allocated, and product baselines [61]. Civil aircraft maintenance support based on PHM is a typical SoS, which integrates key elements of man, machine, material, method, and environment (e.g., aviation materials and spare parts, maintenance organization and personnel, ground support equipment, technical publication, technical support, and maintenance engineering) [62,63].

Consequently, the DoDAF viewpoints are introduced to define the domains of integration, interoperability, and interfaces between constituent systems in such an SoS [61,64]. Wang et al. [23] focused on issues occurred in traditional development process, including incomplete identification of design requirements and inconsistency between development plan and design requirements, and they conduct research on the MBSE development process for urban rapid train based on DoDAF. Chris [24] stated that an MBSE methodology utilizing the guidance offered by DoDAF viewpoints can enhance communication and accelerate iterations of systems engineering practice.

Most previous research has focused solely on models, methods, and algorithms when defining maintenance support, overlooking the functional interactions of PHM system. Additionally, it is recognized that current PHM information, knowledge, and data supporting aircraft maintenance planning are not well integrated, posing challenges for the effective implementation of RCM. To bridge this gap, we propose a structured systems engineering modeling method that integrates the benefits of both multi-viewpoint analysis within DoDAF and systems model described in SysML. The purpose of this research is to integrate PHM information within maintenance support system, thereby maximizing PHM potential and ensuring effective implementation of RCM.

3. Proposed integrated modeling method

3.1 Integrated modeling architecture construction

During the design of a maintenance support system, it is crucial to understand its behaviors, structures, integrations, interactions, and communications with other systems or subsystems. One of the key objectives of this research is to integrate PHM information within maintenance support system to facilitate the effective implementation of RCM.

This research aims to develop a structured, model-based approach that presents essential design information (e.g., requirements, capabilities, operational activities, and interfaces) of the maintenance support system in ways that enhance both understanding and coherence. Additionally, this approach ensures consistency and traceability through the introduction of the DoDAF viewpoints and RFLP framework. In this section, a modeling architecture based on DoDAF and MBSE is presented for integrating PHM information within maintenance support system, as shown in Fig. 1.

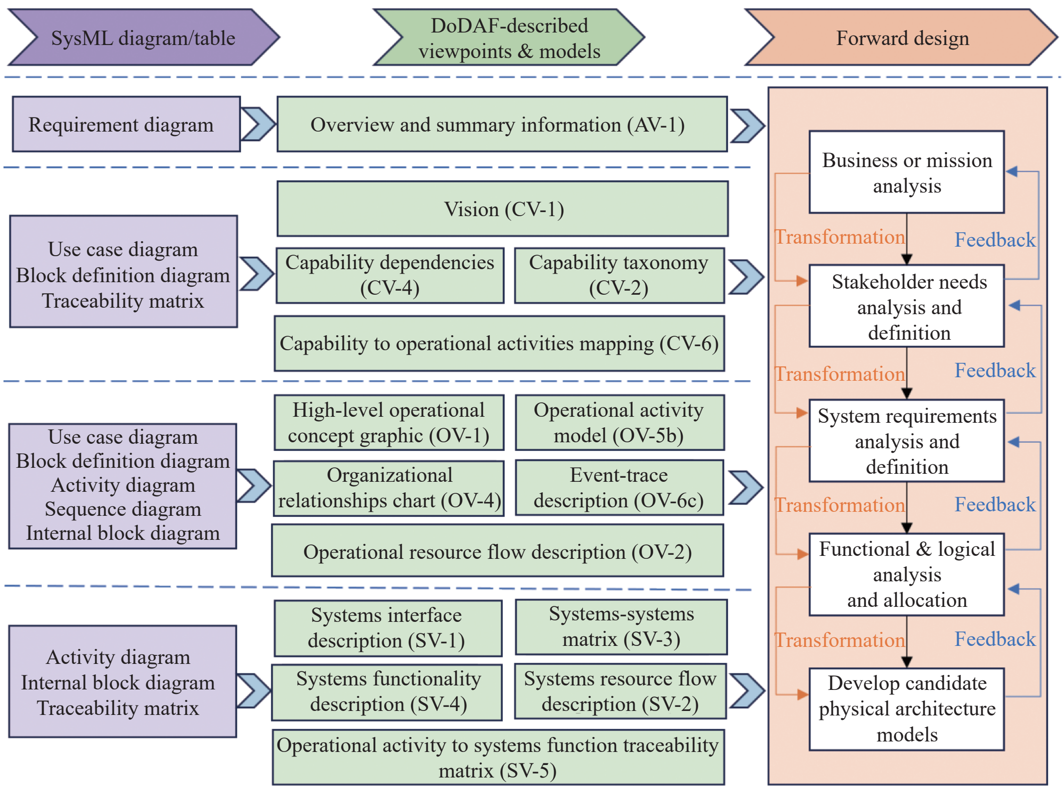

Fig. 1 Integrated modeling architecture based on DoDAF and MBSE

The primary elements of the proposed modeling architecture are the RFLP framework and DoDAF viewpoints. Within the RFLP framework, a common systems model described in SysML ensures that the information related to maintenance support system is consistent and traceable across multiple teams and perspectives [65]. The advantages of adopting the RFLP modeling approach lie in its ability to establish clear traceability links from stakeholder requirements through physical elements, while also providing a clear understanding of the system through both functional and logical decomposition [65]. Throughout the modeling, the traceability of requirements is emphasized by creating traceability matrices linking requirements, functions, and physical elements across multiple viewpoints.

In practice, it is rarely necessary to develop all DoDAF viewpoints, as this may be redundant. The overall conceptual design of the maintenance support system is an important part of top-level design in systems engineering. The DoDAF-described models for the maintenance support system are organized into four different viewpoints: the all viewpoint (AV), capability viewpoint (CV), operational viewpoint (OV), and systems viewpoint (SV). These viewpoints support the major SE processes (e.g., requirements analysis, functional analysis, and architectural design) by providing a structured approach that ensures information and models can be shared with a common understanding across multiple perspectives [66]. The DoDAF-based MBSE approach presented in this paper can help clarify and understand key elements of the maintenance support system from multiple perspectives and establish traceability links through the modeling performed with these viewpoints.

The AV DoDAF-described models provide an overview and summary information (e.g., vision, mission, need, goal, and objective) of the maintenance support system. The CV focuses on the set of capabilities that support the overall mission or vision of maintenance support system. In particular, capability models provide a potentially strategic perspective for taxonomies, interdependencies, mapping, and operational requirements. The OV DoDAF-described models articulate the key activities that enable particular capabilities, operational items, and resource flows exchanged between activities necessary for conducting operations. Utilizing operational models helps to reuse capabilities described in the CV by putting them in the context of an operational scenario and identify the functional scope of capabilities. With the understanding derived from the OV analysis, the SV analyzes the maintenance support system from the perspective of systems elements, functionality, and their interconnections. Furthermore, the systems models also associate systems functions and resource flow elements to operational activities and capability requirements.

In practice, the relationships between these viewpoints are generally iterative and recursive, as shown in Fig. 2. The traceability facilitated by these connections helps maintain consistency and ensures that the designed and implemented maintenance support system align with the overall mission.

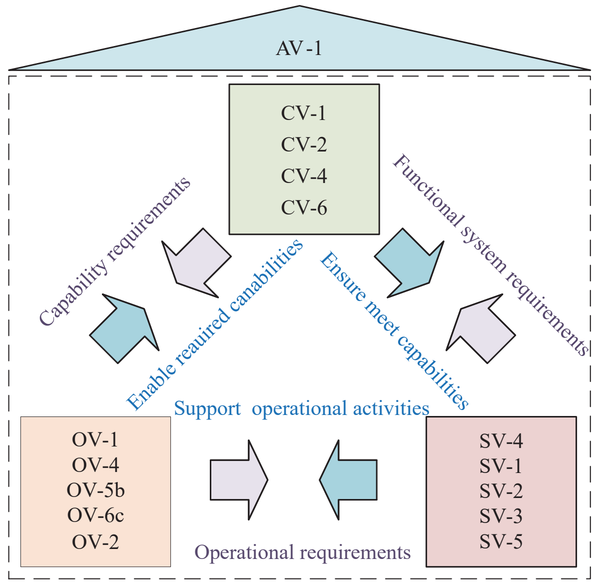

Fig. 2 Overall view of maintenance support

The AV provides an overview and summary of the maintenance support system and the context for other viewpoints. The CV focuses on the capabilities required to achieve the mission or objectives from a strategic perspective. The CV is influenced by the AV as it must align with the overall context described in AV. The OV translates capabilities analyzed in CV into operational terms and describes how they will be achieved operationally. The OV is dependent on the CV as operational activities are designed to support and enable those capabilities. The SV provides a description of the systems, subsystems, and their interactions necessary to support operational activities analyzed in OV and meet capabilities analyzed in CV. Generally, the OV use case analysis treats the maintenance support system as a “black box”, while SV DoDAF-described models are then used for “white box” analysis of the inner operational activities and resource flows of the system itself.

3.2 Integrated modeling logic analysis

The development process of this modeling logic is the development of DoDAF-described models mentioned above. In this paper, the overall modeling process of the maintenance support system design consists of four major steps: (i) analysis of the maintenance support mission; (ii) analysis of the capabilities required to realize the mission; (iii) analysis of the operational tasks and activities needed to enable these capabilities; (iv) analysis of the systems required to support operations and meet capability requirements, as shown in Fig. 3.

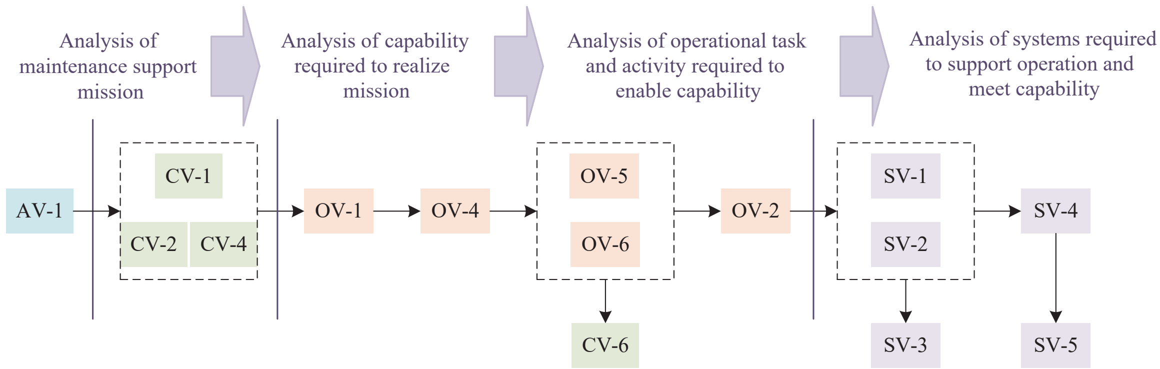

Fig. 3 Overall modeling process of maintenance support system design

Initially, the expectations, needs, goals and objectives of stakeholders are analyzed and described from all viewpoint using the overview and summary information (AV-1) model. This process involves transforming stakeholder requirements into maintenance support requirements and establishing traceability links between system requirements and stakeholder requirements. SysML diagrams such as requirement diagrams, use case diagrams, and traceability matrices will be constructed.

Functional analysis is conducted through multiple models within the capability viewpoint, e.g., capability vision (CV-1), capability taxonomy (CV-2), capability dependencies (CV-4), and capability to operational activities mapping (CV-6). These above CV models entail the allocation of capability requirements to functional modules, as well as the decomposition and derivation of subfunctionalities. The mapping of requirements to functionalities is facilitated by SysML diagrams including use case diagrams and traceability matrices. Furthermore, these diagrams enable the hierarchical functionalities decomposition and the mapping of functionalities to activities. The CV-6 model describes the mapping between required capabilities and operational activities that enable those capabilities. This mapping ensures that operational activities effectively support those capabilities and provides a clear line of sight from strategic mission objectives to operational execution.

With the operational viewpoint's multiple models, including high-level operational concept graphic (OV-1), operational resource flow description (OV-2), organizational relationships chart (OV-4), operational activity model (OV-5b), and event trace description (OV-6c), the logical behavior description between systems and external/internal elements is carried out. This is achieved by analyzing the functional flows, resource flows, and task flows of hierarchical elements as system functionalities are mapped to the logical architecture level. SysML diagrams including activity diagrams, sequence diagrams, state machine diagrams, internal block diagrams, and block definition diagrams will be created to support this analysis.

The construction of multiple models within the systems viewpoint enables the mapping of abstract functional and logical architecture to concrete physical technical solutions. Among these models are systems interface description (SV-1), systems resource flow description (SV-2), systems-systems matrix (SV-3), systems functionality description (SV-4), and operational activity to systems function traceability matrix (SV-5). The key elements derived from functional and logical architecture design process, including interfaces, functionalities, performance, and non-functional requirements, are allocated to system physical elements in a manner consistent with the functional and logical architecture. Notably, the SV-5a model provides traceability between system functions described in SV-4 and operational activities specified in OV-5b. This ensures that the system functions are designed to enable the operational activities necessary to fulfill the identified capabilities.

Finally, a recursive and cross-iterative analysis of the various DoDAF-described models is performed through feedback. This feedback ensures traceability and consistency between the physical and functional/logical architectures, system requirements, and stakeholder requirements, thereby reinforcing the integrity and effectiveness of the maintenance support system design process.

4. Case study

The complete process illustrating the proposed method is given with an example of a maintenance support system based on PHM information.

4.1 Requirement modeling based on requirements and use cases

The initial step involves a meticulous and comprehensive identification of the maintenance support system integration workflow through an in-depth analysis of stakeholders' requirements. The AV-1 model is developed using requirement diagrams, serving as a strategic blueprint for the initial phase of designing and developing the maintenance support system based on PHM, as shown in Fig. 4.

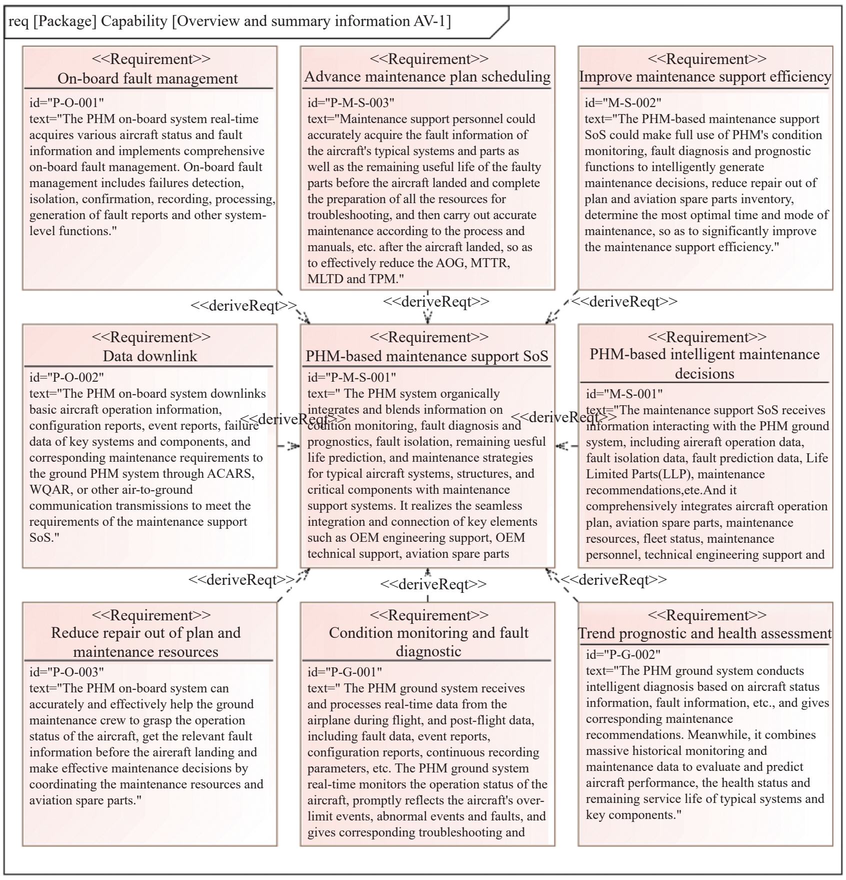

Fig. 4 Overview and summary information AV-1

Building upon the AV-1 model, a top-down, use case-driven, and incremental modeling strategy is employed to ensure continuous alignment with stakeholder requirements. From the perspective of the capabilities required to achieve the maintenance support mission, a capability blueprint is crafted, which captures the needs, goals, and objectives of stakeholders across the entire operational scenario. These structured definitions are then transformed into system requirements and use cases. The CV-1 model is constructed as shown in Fig. 5.

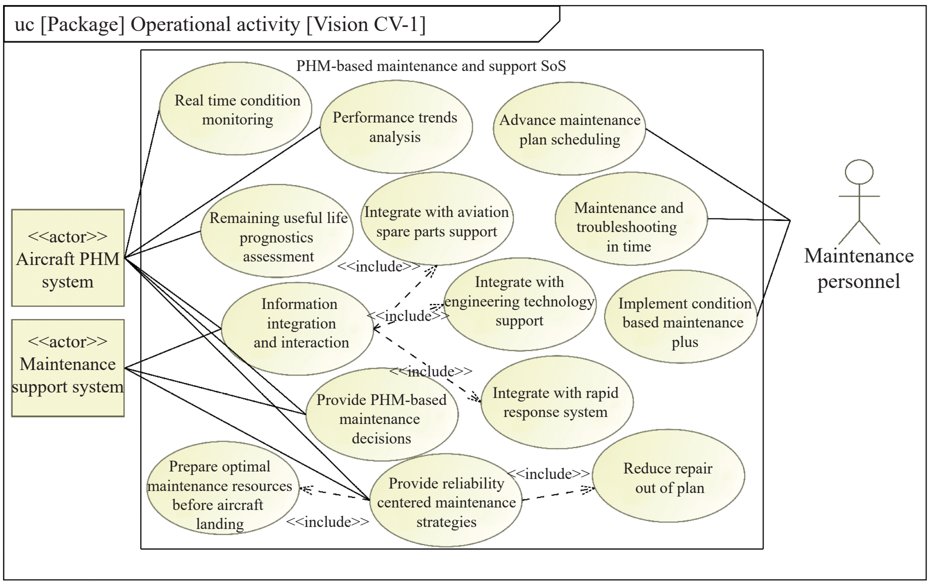

Fig. 5 Vision CV-1

The CV-1 model encapsulates the key elements and system behaviors involved in the integration process of the maintenance support system. Initially, the granularity of a newly created use case might be overly broad and requires refinement. To address this, activity diagrams are employed for flow-oriented behavioral modeling, while sequence diagrams are utilized for message-driven behavioral modeling, enabling a systematic refinement of the scenarios. As the modeling process progresses, use cases are incrementally refined through activity and interaction modeling, contributing to a more detailed and concrete definition.

For each capability vision in the CV-1 model, hierarchical decomposition is systematically conducted by enumerating various operational scenarios and creating use cases. This process establishes hierarchical relationships among capabilities, transforming abstract capabilities into specific sub-capabilities. The CV-2 model is presented, as shown in Fig. 6. In CV-2 model, both generalization and association relationships are used to represent the hierarchical and interconnected relationships among capabilities. For example, real-time condition monitoring can be further decomposed into lower-level sub-capabilities, including threshold exceedance monitoring, flight operational quality assurance, anomaly event monitoring, fault monitoring, parameter monitoring, and fuel consumption monitoring.

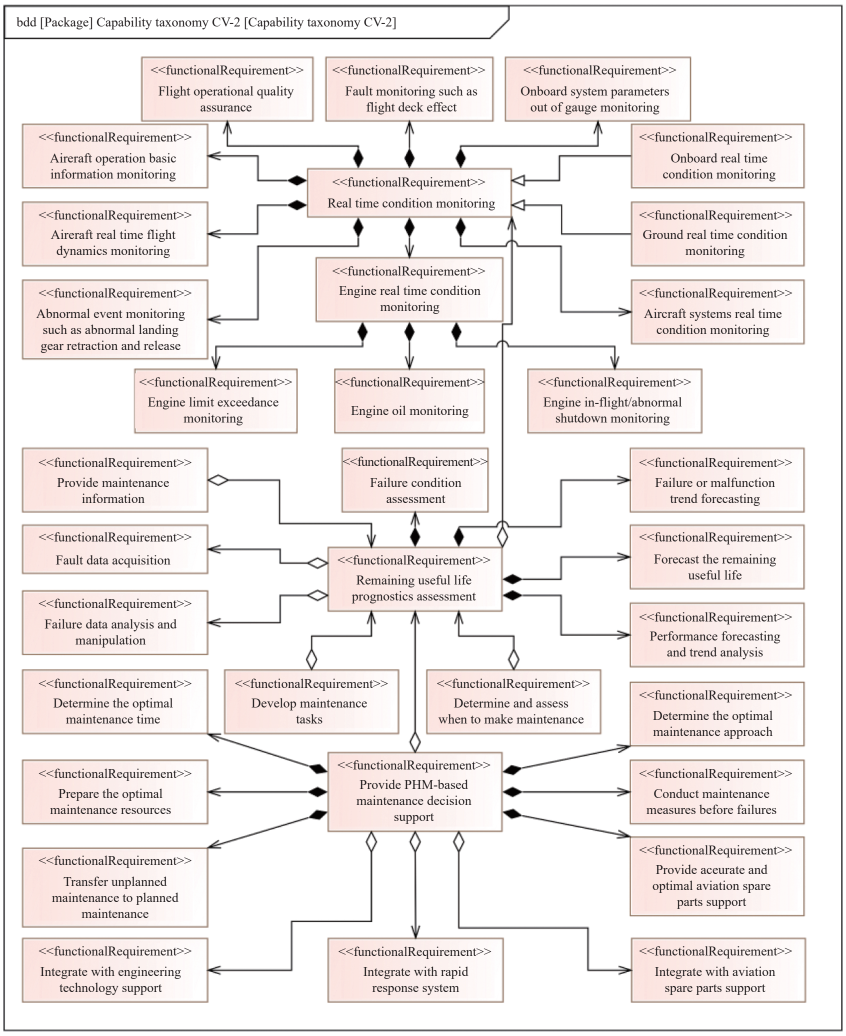

Fig. 6 Capability taxonomy CV-2

Based on the capability taxonomy relationships described in the CV-2 model, the CV-4 model can be developed to depict the dependencies and generalization relationships between capabilities and sub-capabilities. Due to space constraints, this paper provides only a summary of the interconnections between capabilities associated with PHM-based maintenance decision-making rather than presenting all the details of the CV-4 model. For instance, PHM-based maintenance decision-making relies on fault diagnosis, key component failure prediction, performance trend prediction, and health status assessment. Furthermore, failure and performance trend prediction are critical drivers for health status assessment, while fault diagnosis, failure prediction, and performance trend prediction are dependent on condition monitoring.

4.2 Functional architecture modeling based on behavior and use cases

Subsection 4.1 focuses on a detailed analysis and modeling of stakeholder requirements and system functional requirements, highlighting maintenance support capabilities, operations, and functionalities from the perspective of the problem domain. Moving forward, we now proceed with a systematic functional and logical analysis, as well as a behavioral description, within the solution domain. This process involves the allocation and decomposition of constraints, interfaces, functionalities, and performance metrics across each system element, thereby laying a foundation for detailed architectural design.

The core advantage of PHM system lies in its seamless integration of on-board health status information with the ground-based maintenance support SoS. Such integration is crucial as it enables the generation of autonomous logistic support decisions and rapid maintenance strategies, significantly enhancing the system's proactive and rapid response capabilities. These transformative capabilities drive innovative shifts in traditional maintenance models, transitioning from reactive to predictive maintenance.

The interaction process primarily involves the transmission of critical data and information from the PHM system to the maintenance support SoS. This includes quick access recorder (QAR) data, aircraft operational data, fault isolation information, and maintenance prediction information. Upon receiving this data and information, the maintenance management system considers key factors such as aviation spare parts availability, maintenance resources, and original equipment manufacturer engineering technical support. Based on this comprehensive analysis, the system generates rapid, precise, and high-quality maintenance plans tailored to the aircraft's health state. Subsequently, the engineering and technical departments carry out proactive maintenance support activities informed by PHM insights. Feedback on maintenance data, including data from aircraft and component repairs, is then provided to the PHM system as historical maintenance data, achieving a closed-loop management.

To illustrate this integration, this paper develops the OV-1 model, depicting PHM-based unscheduled maintenance as a typical scenario, as shown in Fig. 7.

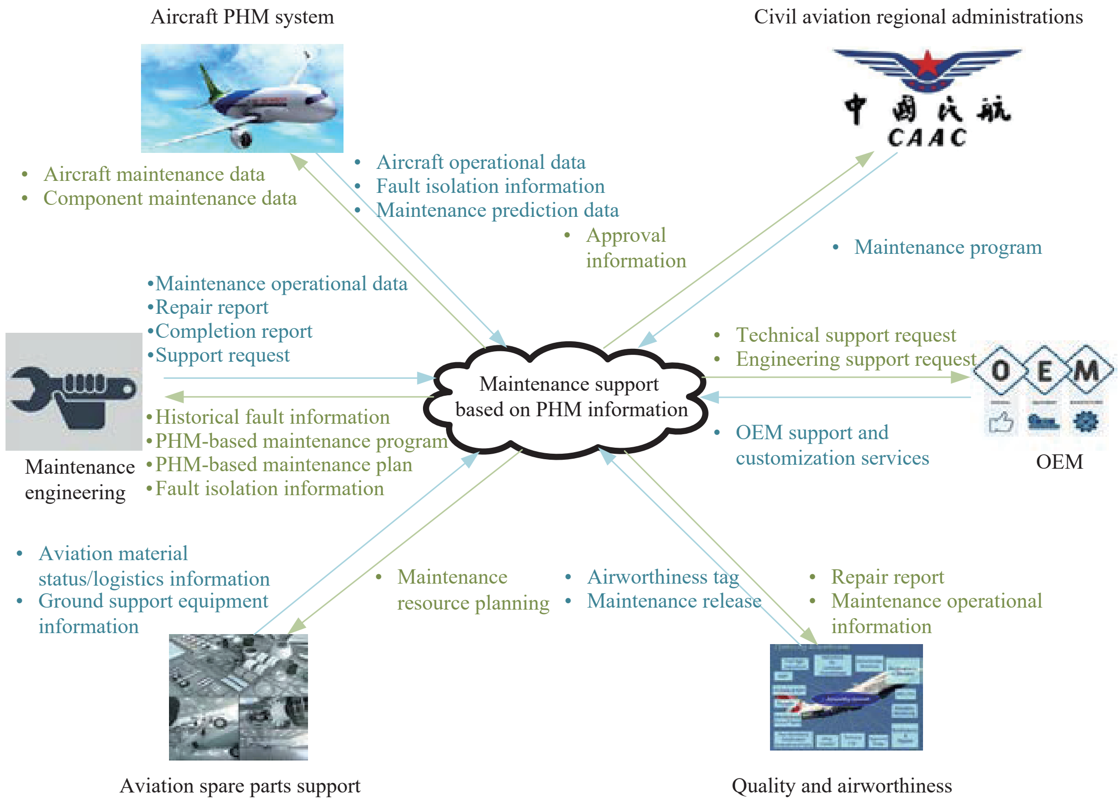

Fig. 7 High level operational concept graphic OV-1

It becomes evident that the OV-4 model is highly suitable for guiding the initial design and conceptualization from a strategic, top-level perspective. This model serves as a foundational blueprint for defining operational structures and mapping out synergies among maintenance support nodes, organizations, and performers. The OV-4 model of maintenance support system based on PHM is presented, as shown in Fig. 8.

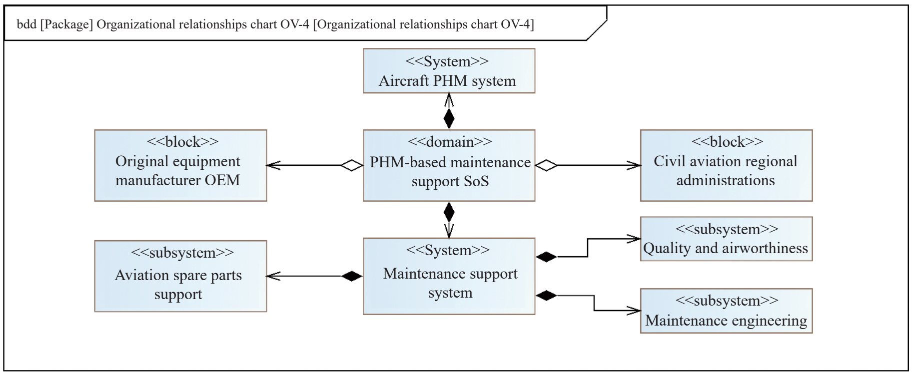

Fig. 8 Organizational relationships chart OV-4

The aircraft PHM system, OEMs, maintenance organization, rapid response platform, maintenance management platform, and civil aviation regional administrations are involved in the overall maintenance support process. Among these entities, the maintenance organization can be further divided into specialized departments, including aviation material support, maintenance engineering, training, and quality and airworthiness. The maintenance engineering department, in turn, can be subdivided into organizational structures such as the maintenance control center, maintenance base, line maintenance branch, and overnight outstation. Each of these units plays a critical and interconnected role within the overall maintenance support framework, contributing to a cohesive and efficient system by ensuring seamless coordination and execution of maintenance support tasks.

Next, under the maintenance support concepts and scenarios described in the OV-1 model, the resource flows transferred between the maintenance support nodes defined in the OV-4 model are described to further clarify capability requirements and boundaries. Typically, the OV-2 model is created first, followed by the OV-5b model, as these two models are complementary and interdependent. The OV-2 model primarily focuses on the interaction ports or interface information related to resource flows between internal components of the maintenance support nodes or systems. In contrast, the OV-5b model is more concerned with detailing the specific activities and processes necessary to accomplish maintenance support tasks. It is important to note that after completing the OV-6c model, the OV-2 model should be further refined. This refinement ensures that the interaction message or events defined in the OV-6c model can be effectively transmitted and exchanged between maintenance support nodes, thereby achieving the true flow of resource flows across nodes. For a clear and comprehensive representation of resource interactions, the OV-2 model is constructed in the form of an internal block diagram, as shown in Fig. 9.

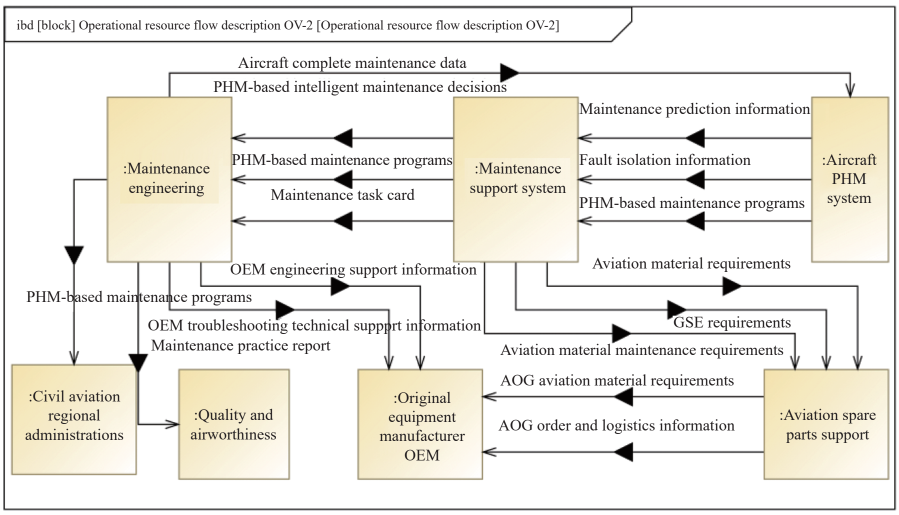

Fig. 9 Operational resource flow description OV-2

Following the high-level operational concept outlined in the OV-1 model and the resource flow information described in the OV-2 model, the operational activities of maintenance support, along with their control logic and resource flow dynamics, are systematically categorized. As an illustrative example, a model for PHM-based unscheduled maintenance, represented by the OV-5b model, has been developed and is depicted in Fig. 10. Call behavior actions are created within the activity to model the decomposition of high-level behaviors, while activity partitions are utilized to associate behaviors with structures. The PHM-based unscheduled maintenance activity incorporates two call behavior actions, which trigger the behavior models for maintenance prediction and maintenance resource preparation. By allocating behavioral activities to execution nodes, it becomes clear which behaviors are responsible for specific structures. This also identifies the system interfaces and functional activities involved in the subsequent creation of SV models, facilitating the integrated design work of various systems in later stages.

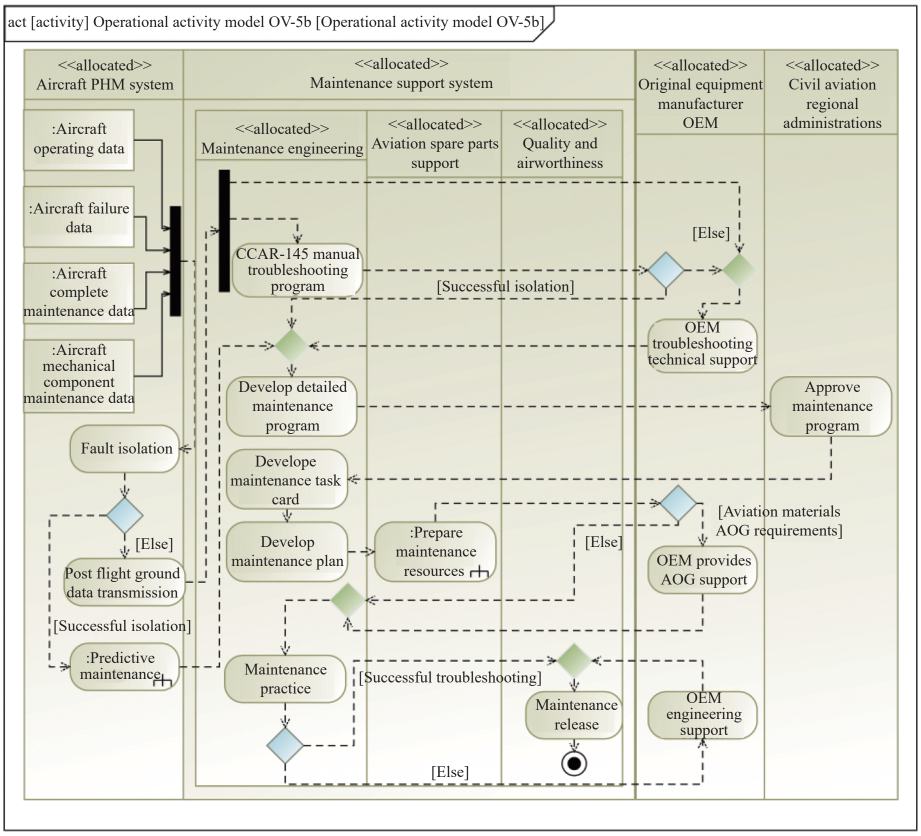

Fig. 10 Operational activity model OV-5b

Subsequently, the CV-6 model is developed to depict the mapping relationship between the maintenance support activities planned in the OV-5b model and the capabilities defined in the CV-2 model, as shown in Fig. 11. The CV-6 model establishes a traceability relationship between the CV and OV viewpoints. Through the model, it is possible to verify whether the planned functional activities fully or partially meet the required capability requirements.

The objective of integration is to achieve proactive maintenance based on PHM, ensuring the efficiency, accuracy, and effectiveness of completing maintenance support tasks. For service-oriented conceptual modeling, the OV-6c model enables effective analysis and validation of the completeness and correctness of information interactions throughout maintenance support activities. Moreover, the OV-6c model refines the operational activities in the OV-5b model into multiple scenarios by detailing the events and temporal relationships of resource interactions among executors, thereby helping to verify the completeness and correctness of OV-5b. The OV-6c model is developed using sequence diagrams, as shown in Fig. 12.

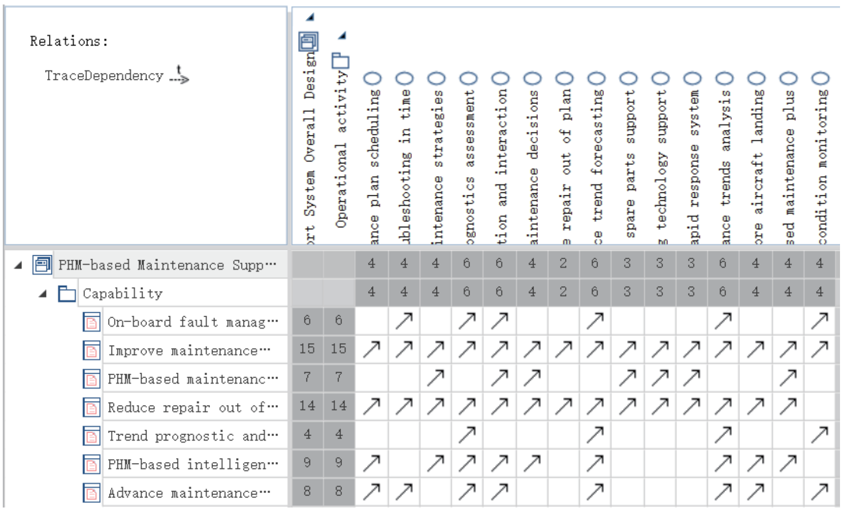

Fig. 11 Capability to operational activities mapping CV-6

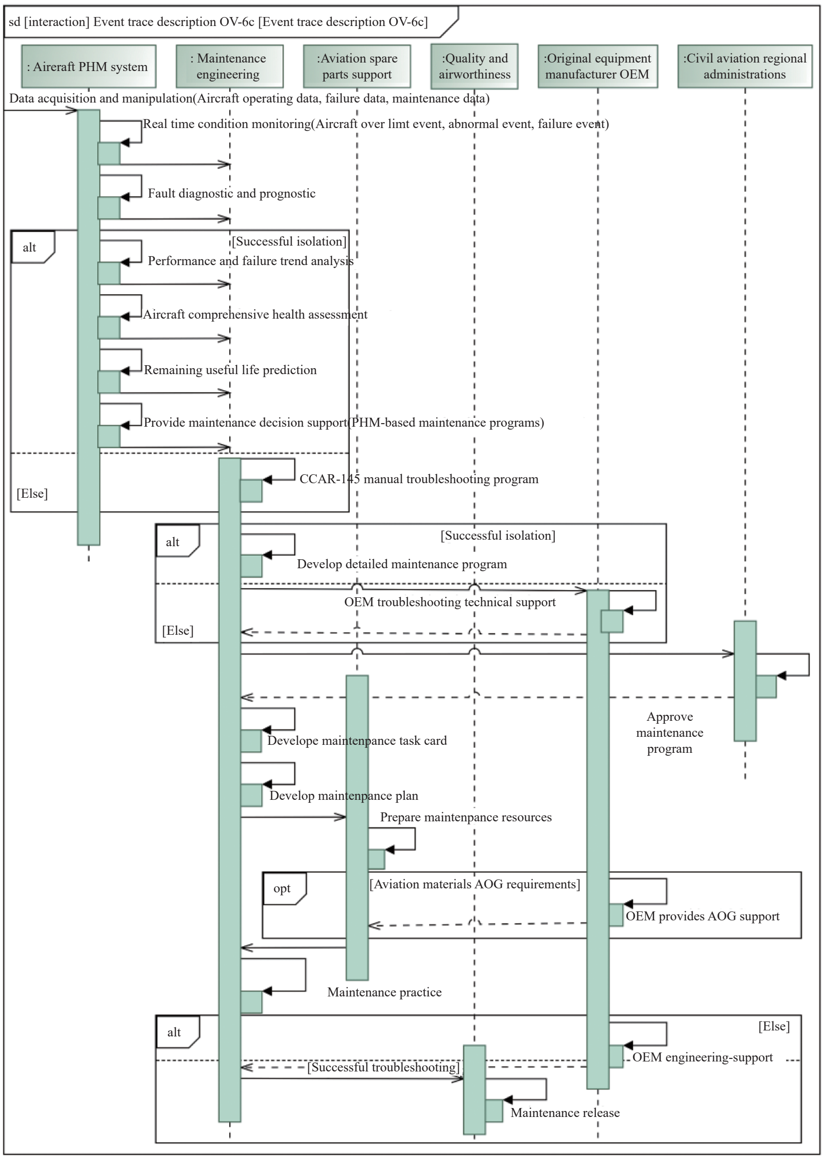

Fig. 12 Event trace description OV-6c

4.3 Functional modeling based on behavior and structure

The majority of previous modeling efforts have primarily focused on the logical specifications for the integration of PHM system and maintenance support SoS, with relatively little emphasis on physical specifications. Therefore, after completing the creation of models under the AV, CV, and OV viewpoints, it becomes necessary to examine the architecture from the perspective of implementers and integrators, and the SV viewpoint makes this possible.

Systems achieve functionality through activities or processes, and these activities are linked to specific systems as described in the OV-5b model. By integrating the operational activities, the SV-4 model is developed to further clarify the functions of performers and systems, as shown in Fig. 13. It is important to note that operational activities and system functions are essentially the same in nature: the former describes the logical specifications of what to do, while the latter details the physical specifications of how to do it.

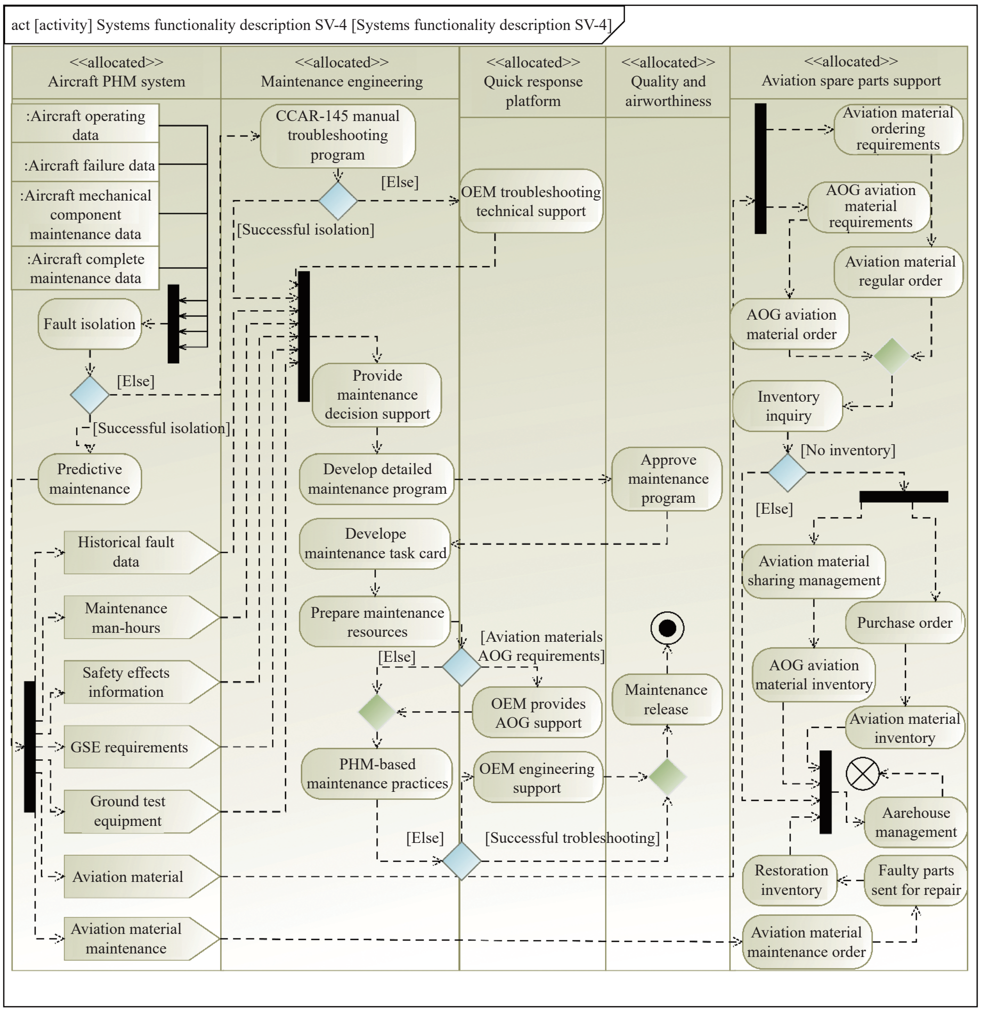

Fig. 13 Systems functionality description SV-4

Through the functionality descriptions provided in the SV-4 model, the resource flows exchanged between systems during the integrated implementation of the maintenance support system become clearer and more explicit. Building on the physical deployment framework of the integrated maintenance support system, the SV-4 model serves as a foundation for identifying and detailing the system functions executed by various performers. By incorporating these functions, a systematic categorization of interface information exchanged between systems is conducted, contributing to the construction of the SV-2 model for the integration of aircraft PHM system and maintenance support SoS, as shown in Fig. 14.

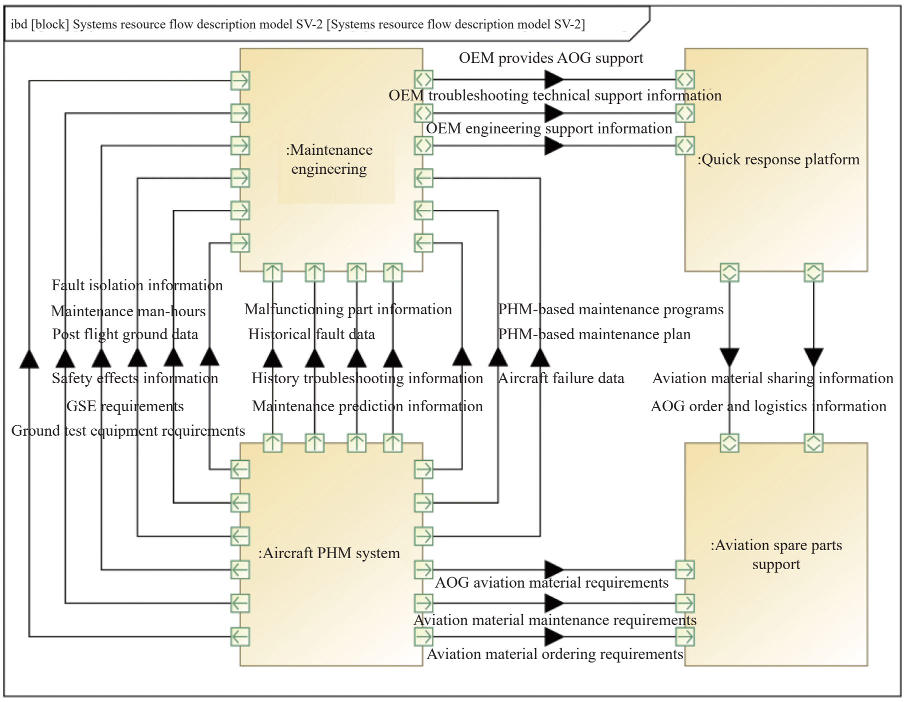

Fig. 14 Systems resource flow description SV-2

The resource flows transmitted from PHM system to maintenance management system include major categories such as QAR data, aircraft operational data, fault data, fault isolation information, and maintenance prediction information. The maintenance prediction information encompasses a range of details, including maintenance items, maintenance task codes, man-hour forecast information, aviation material forecast information, ground support equipment forecast information, and testing equipment forecast information. Conversely, the resource flows transmitted from maintenance management system to PHM system primarily include overall aircraft maintenance data and component maintenance data.

By analyzing the traceability relationships between maintenance support activities in the OV-5b model and system functions in the SV-4 model, the SV-5a model can be established to verify whether the designed system functions fully or partially support the required activities. Similarly, the SV-5b model can be further established based on the SV-2 and OV-5b models. For brevity, the SV-5a model is presented as an example for illustration, as shown in Fig. 15. The row elements represent system functions, the column elements are operational activities, and the cross cells indicate that the system functions support operational activities. This allows for an intuitive analysis of the gap between system design and task requirements, enabling a quick determination of whether the designed system or system function has the ability to complete maintenance support tasks.

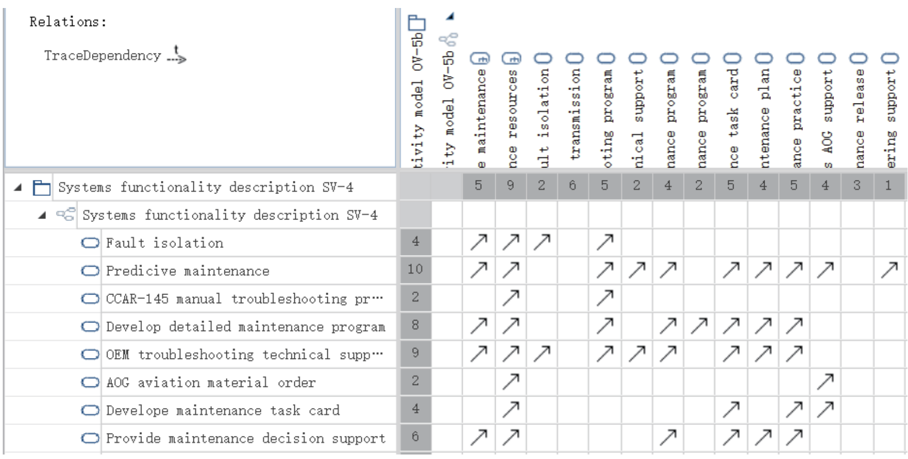

Fig. 15 Operational activity to systems function traceability matrix SV-5a

4.4 Logic simulation and verification

The traditional DBSE design pattern can not realize virtual simulation and verification at the logical level, which easily leads to the accumulation of problems in the design process, resulting in a snowball effect. In contrast, the MBSE method supports iterative and incremental verification and validation throughout the system design lifecycle, reducing the risk of design conflicts and inconsistencies. In this study, SysML and Rhapsody are employed to develop both static and dynamic simulation models that support the PHM integration. Furthermore, multiple rounds of visual simulation and verification are conducted.

To enhance and refine the integrated modeling process, an incremental modeling approach is utilized, combining iterative processes with simulation results. Issues identified through simulation analysis, such as repeated requirements, invalid call behavior actions, and resource flow node errors, are addressed through timely modifications. Following each modification, further verification is performed, and the results are documented and presented, as shown in Fig. 16. The simulation results demonstrate that the designed component functions can work collaboratively, ensuring both functional completeness and logical consistency of the architecture models.

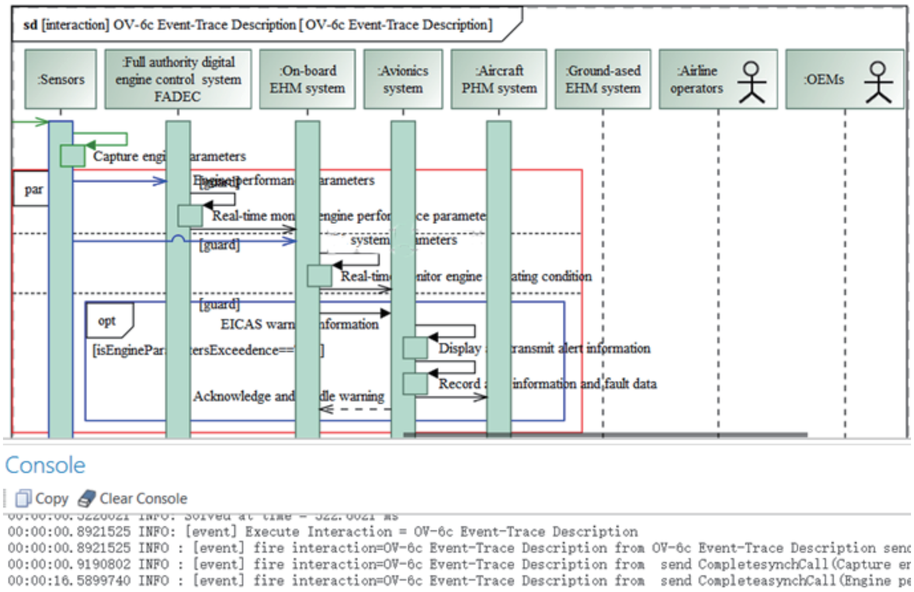

Fig. 16 Logic simulation and verification results

5. Conclusions

In light of the integration requirements and engineering challenges inherent to civil aircraft PHM and maintenance support, this paper proposes an integrated modeling method based on DoDAF and MBSE. The integration modeling architecture and logic are presented, followed by examples illustrating the construction of models for requirements, resource flow, activities, and interfaces. Furthermore, traceability relationships are established to ensure logical consistency and functional integrity. The model simulation results demonstrate that the proposed approach not only enhances model consistency and traceability but also provides a comprehensive, multidimensional representation of model information.

In future work, the integration of PHM with other systems will be continuously explored. Aviation material support and engine condition monitoring will be considered to promote the civil aircraft PHM integration technology in practical engineering scenarios.

References

[1] FANG Z, LI W, SU L, et al. Prognostics and health management based on next-generation technologies: a literature review. Applied Sciences-Basel, 2024, 14(14): 6120.

[2] CHIARA F, YASAMIN E, MARIO L, et al. Ontologies for prognostics and health management of production systems: overview and research challenges. Journal of Intelligent Manufacturing, 2025, 36: 2223−2253.

[3] QIU J, TAN X D, LIU G J, et al. Test selection and optimization for PHM based on failure evolution mechanism model. Journal of Systems Engineering and Electronics, 2013, 24(5): 780−792.

[4] ZIO E. Prognostics and health management methods for reliability prediction and predictive maintenance. IEEE Trans. on Reliability, 2024, 73(1): 41.

[5] XU J P, XU L. Health management based on fusion prognostics for avionics systems. Journal of Systems Engineering and Electronics, 2011, 22(3): 428−436.

[6] SAE International Group. Guidelines for integrating typical engine health management functions within aircraft systems. https://doi.org/10.4271/AIR4061C.

[7] LIU B W, WANG J Y, CHI C Z, et al. Research and visual realization of civil aircraft PHM maintenance support system based on STK. Proc. of the Conference on 2019 Prognostics and System Health Management, 2019: 138−142.

[8] FERRI F A S, RODRIGUES L R, GOMES J P P, et al. Combining PHM information and system architecture to support aircraft maintenance planning. Proc. of the Conference on 7th Annual IEEE International Systems Conference, 2013: 60−65.

[9] LI T, CHANG C. Research on PHM technology application in maintenance support for armored vehicle command control and communication system. Proc. of the Conference on Quality, Reliability, Risk, Maintenance and Safety Engineering, 2012: 726−730.

[10] JIA Z Y, ZENG Z Y, XU Z H, et al. Models for evaluating maintenance support capability of aviation equipment based on PHM. Proc. of the Conference on Prognostics and System Health Management, 2012. DOI: 10.1109/PHM.2012.6228946.

[11] CAMCI F, VALENTINE G S, NAVARRA K. Methodologies for integration of PHM systems with maintenance data. Proc. of the IEEE Conference on Aerospace, 2007. DOI: 10.1109/AERO.2007.352917.

[12] TU F, GHOSHAL S, LUO J B, et al. PHM integration with maintenance and inventory management system. Proc. of the Conference on Aerospace, 2007. DOI: 10.1109/AERO.2007.352918

[13] ALIREZA A, MARKUS K, TORBJORN F, et al. Integration of RCM and PHM for the next generation of aircraft. Proc. of the IEEE Conference on Aerospace, 2009: 3798−3806.

[14] FU S, AVDELIDIS N P. Prognostic and health management of critical aircraft systems and components: an overview. Sensors, 2023, 23(19): 8124.

[15] YE Q F, SHEN S L, MA L L. Research on the model integration in aircraft PHM development. Proc. of the Conference on Global Reliability and Prognostics and Health Management, 2020. DOI: 10.1109/PHM-Shanghai49105.2020.9280992.

[16] TU J L, TAO Q X, LI L. Construction of large data driven maintenance support system for trainers under the background of civil military integration. Proc. of the Conference on the 8th Logistics and Systems Engineering, 2019: 178−187.

[17] GAO T, CHEN P, HAN M. Study on the influence of PHM technology on aircraft maintenance support mode. Proc. of Conference on the 10th IEEE Prognostics and System Health Management, 2019. DOI: 10.1109/PHM-Qingdao46334.2019.8942925.

[18] FU X Y, ZHONG S S, ZHU J M. Civil aeroengine health management and maintenance decision support system: development and application. Proc. of the Conference on AIAA Aviation, Technology, Integration, and Operations, 2013: 2593−2599.

[19] CHEN J W, CHEN Y F, HU Z C, et al. A semantic ontology-based approach to support model-based systems engineering design for an aircraft prognostic health management system. Frontiers in Manufacturing Technology, 2022, 2: 886518.

[20] MAZEIKA D, MORKEVICIUS A, ALEKSANDRAVICIENE A. MBSE driven approach for defining problem domain. Proc. of the Conference on the 11th IEEE System of Systems Engineering, 2016. DOI: 10.1109/SYSOSE.2016.7542911.

[21] LU J Z, TSINARAKIS G, SARANTINOUDIS N, et al. A semantic model-based systems engineering approach for assessing the operational performance of metal forming process. Computers & Industrial Engineering, 2024, 190: 110042.

[22] WANG S K, LI J Z, ZHAO J T, et al. Research on architecture design and description methods based on DoDAF. Proc. of the Conference on the 11th Signal and Information Processing, Network and Computers, 2024: 366−372.

[23] WANG H F, ZHANG J G, LIU H J, et al. MBSE development process of urban rapid train based on DODAF. Proc. of Conference on 6th Electrical Engineering and Information Technologies for Rail Transportation, 2024: 564−571.

[24] CHRIS P. Model based systems engineering with Department of Defense Architectural Framework. Systems Engineering, 2011, 14(3): 305–326.

[25] FANG Z M, ZHOU X Z, SONG A N. Architectural models enabled dynamic optimization for system-of-systems evolution. Complexity, 2020, 1: 7534819.

[26] LI T, LOCKETT H, LAWSON C. Using requirement-functional-logical-physical models to support early assembly process planning for complex aircraft systems integration. Journal of Manufacturing Systems, 2020, 54: 242–257.

[27] GUENOV M D, MOLINA C A, VOLOSHIN V, et al. Aircraft systems architecting-a functional-logical domain perspective. Proc. of the Conference on AIAA Aviation, Technology, Integration, and Operations, 2016. DOI: 10.2514/6.2016−3143.

[28] BIGGIO L, KASTANIS I. Prognostics and health management of industrial assets: current progress and road ahead. Frontiers in Artificial Intelligence, 2020, 3: 578613.

[29] ENRICO Z. Prognostics and health management (PHM): where are we and where do we (need to) go in theory and practice. Reliability Engineering & System Safety, 2022, 218: 108119.

[30] HU Y, MIAO X W, SI Y, et al. Prognostics and health management: a review from the perspectives of design, development and decision. Reliability Engineering & System Safety, 2022, 217: 108063.

[31] XIA T B, DONG Y F, XIAO L, et al. Recent advances in prognostics and health management for advanced manufacturing paradigms. Reliability Engineering & System Safety, 2018, 178: 255–268.

[32] MICHELE C, PIERO B, ENRICO Z. Challenges to IoT-enabled predictive maintenance for Industry 4.0. IEEE Internet of Things Journal, 2020, 7(5): 4585−4597.

[33] KWON D, HODKIEWICZ M R, FANS J, et al. IoT-based prognostics and systems health management for industrial applications. IEEE Access, 2016, 4: 3659–3670.

[34] YANG L, SUN Q Z, YE Z S. Designing mission abort strategies based on early-warning information: application to UAV. IEEE Trans. on Industrial Informatics, 2020, 16(1): 277–287.

[35] XIAO L, SONG S L, CHEN X H, et al. Joint optimization of production scheduling and machine group preventive maintenance. Reliability Engineering & System Safety, 2016, 146: 68–78.

[36] MOHAMMADREZA T, ELIAS T, MASDI M, et al. Performance-based health monitoring, diagnostics and prognostics for condition-based maintenance of gas turbines: a review. Applied Energy, 2017, 198: 122–144.

[37] GUILLEN A J, CRESPO A, MACCHI M, et al. On the role

of prognostics and health management in advanced maintenance systems. Production Planning & Control, 2016, 27(12): 991–1004.

[38] RATH N, MISHRA R K, KUSHARI A. Aero engine health monitoring, diagnostics and prognostics for condition-based maintenance: an overview. International Journal of Turbo & Jet-Engines, 2024, 40(S1): 279–292.

[39] KWAKYE A D, JENNIONS I K, EZHILARASU C M. Platform health management for aircraft maintenance-a review. Proceedings of the Institution of Mechanical Engineers Part G-Journal of Aerospace Engineering, 2024, 238(3): 267–283.

[40] YAN H S, ZUO H F, SUN J Z, et al. Cost effectiveness evaluation model for civil aircraft maintenance based on prognostics and health management. Proc. of the Conference on Sensing, Diagnostics, Prognostics, and Control, 2017: 161−167.

[41] ALASWAD S, XIANG Y S. A review on condition-based maintenance optimization models for stochastically deteriorating system. Reliability Engineering & System Safety, 2017, 157: 54–63.

[42] CHEN M, XU L, CHENG W. Research on equipment maintenance support information system for PHM. Proc. of Conference on Network, Communication, Computer Engineering, 2018: 651−656.

[43] KOBBACY A H K, MURTHY D N P. Complex system maintenance handbook. London: Springer Verlag, 2008.

[44] YAN H S, ZUO H F, TANG, J Q, et al. Predictive maintenance framework of the aircraft system based on PHM information. Proc. of the Conference on Advanced Reliability and Maintenance Modeling, 2020. DOI: 10.1109/APARM49247.2020.9209454.

[45] GALLEGO G S, GEJO G J, GARCIA G M. Development of a maintenance and spare parts distribution model for increasing aircraft efficiency. Applied Sciences-Basel, 2021, 11(3): 1–21.

[46] SAE International Group. Guidelines for integrating typical engine health management functions within aircraft systems. http://doi.org/10.4271/air4061c.

[47] MADNI A M, SIEVERS M. Model-based systems engineering: motivation, current status, and research opportunities. Systems Engineering, 2018, 21(3): 172–190.

[48] MADNI A M, SIEVERS M. Model-based systems engineering: motivation, current status, and needed advances. Proc. of the Conference on Disciplinary Convergence in Systems Engineering Research, 2017: 311−325.

[49] INCOSE. Systems Engineering Vision 2020. https://www.mendeley.com/catalog/systems-engineering-vision-2020-8.

[50] INCOSE. Systems Engineering Vision 2035. https://sevisionweb.incose.org.

[51] WANG Y B, STEINBACH T, KLEIN J, et al. Integration of model based system engineering into the digital twin concept. Proc. of the 31st CIRP Design Conference, 2021: 19−24.

[52] MCMILLAN C, LEE L, RUSSELL D, et al. Verification and validation of model-based systems requirements and design leveraging formal methods to increase development assurance. Proc. of the AeroTech Conference and Exhibition, 2024. DOI: 10.4271/2024−01-1917.

[53] KLEINER S, KRAMER C. Model based design with systems engineering based on RFLP using V6. Proc. of the 23rd CIRP Design Conference, 2013: 93−102.

[54] LANZOTTI F G, MARZULLO D, DI GIRONIMO G. RFLP approach to DTT divertor fixation system design using the 3DExperience platform. Proc. of the Conference on the 3rd Italian Association of Design Methods and Tools for Industrial Engineering, 2024: 289−297.

[55] SEABRIDGE A, MOIR I. Design and development of aircraft systems. 3rd ed. Chichester: John Wiley & Sons, 2019.

[56] SAE International Group. Guidelines for development of civil aircraft and systems. http://doi.org/10.4271/arp4754a.

[57] MENSHENIN Y, MORDECAI Y, CRAWLEY E F, et al. Handbook of model-based systems engineering. Switzerland: Springer Cham, 2022.

[58] BORKY J M, BRADLEY T H. Effective model-based systems engineering. Switzerland: Springer Cham, 2018.

[59] WEILKIENS T, LAMM J G, ROTH S, et al. Model-based system architecture. 2nd ed. Chichester: John Wiley & Sons, 2022.

[60] GUO Y Q, WANG Z R, ZHAO H, et al. A unified SoS and system architecture modeling framework based on grid-type MBSE methodology. Proc. of the Conference on the 14th Complex Systems Design and Management, 2023: 96−104.

[61] GARRETT R K, ANDERSON S, BARON N T, et al. Managing the interstitials, a system of systems framework suited for the ballistic missile defense system. Systems Engineering, 2011, 14(1): 87–109.

[62] BAI Y, LIU X, ZHOU L J, et al. Aviation equipment maintenance support system based on KELM effectiveness evaluation. Proc. of Conference on the 2nd Artificial Intelligence and Information Systems, 2021: 97.

[63] ZHUANG C B, LIU Z W, LIU J H, et al. Digital twin-based quality management method for the assembly process of aerospace products with the grey-markov model and apriori algorithm. Chinese Journal of Mechanical Engineering, 2022, 35(5): 66–86.

[64] ZHAO Q S, CHEN Q H, QIAN Q Y, et al. Architecture design of the anti-aircraft system based on architecture framework. Proc. of the IEEE International Systems Conference, 2023. DOI: 10.1109/SysCon53073.2023.10131083.

[65] OMOAREBUN E N, CIMTALAY S, MAVRIS D. Formalizing the decomposition process between elements in the RFLP framework using axiomatic design theory. Proc. of Conference on AIAA Aviation and Aeronautics Forum and Exposition, 2023. DOI: 10.2514/6.2023−3771.

[66] U.S. Department of Defense. The DoDAF architecture framework version 2.02. https://dodcio.defense.gov/library/dod-architecture-framework.