Based on the MBSE EMU Train Control Management Systems Requirements Analysis and Verification

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Abstract. Addressing the issues of low development efficiency and lengthy design cycles associated with document-based approaches in the design of Train Control Management Systems (TCMS), this paper introduces Model-Based System Engineering (MBSE) during the TCMS requirement analysis process. Guided by the needs of TCMS stakeholders, this study defines, captures, decomposes, and traces requirements, utilizing M-Design modeling tools to construct models of requirements, functions, and logic. As a case study, the paper examines the simulation of train door control logic based on modeling, with a focus on the network control system's regulation of door status. The results indicate that, guided by the needs of network control system stakeholders, a functional requirement was unearthed: "The network control system can regulate train doors." Using this requirement as an example, the study conducts contextual analysis of the target system, clarifying information exchange and logical relationships between systems. Ultimately, leveraging model-driven concepts and CSM modeling tools to configure UI interfaces, a simulation model is constructed to mimic the train door control process, visually demonstrating the door opening and closing mechanism, thus ensuring that the analyzed requirements are met. This reflects the advantages of MBSE design methods in the early verification and rapid simulation stages of network control system design, significantly enhancing research and development efficiency.

Keywords: Emu; Train Control Management Systems (TCMS); Control logic; MBSE

1 Introduction

As technology advances, complex systems are now widely used in various sectors such as aerospace and rail transport. These intricate systems consistently integrate multidisciplinary knowledge encompassing mechanical, electrical, control, and software domains. To successfully implement these complex systems, system engineering has been introduced as an interdisciplinary approach. System engineering has shifted from a documentation-based to a model-based paradigm due to the numerous advantages models offer, including enhanced comprehensibility and traceability [1]. The Train Control and Monitoring System (TCMS) is one of the critical technologies for

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high-speed trains. It is a complex and expansive system responsible for various tasks, such as train control, network information transmission, operational status monitoring, and fault diagnosis, serving as a vital safeguard for the safe operation of high-speed trains. The analysis of train requirements determines the final product quality of the TCMS development. Incomplete capture, inadequate analysis, unstringent confirmation, imprecise allocation, and insufficient validation of requirements can lead to significant discrepancies between the actual and target systems, resulting in costly modifications later on. In recent years, many scholars have researched requirements using Model-Based Systems Engineering (MBSE). Wang Baomin et al. [2] proposed an MBSE-based train requirement management method that ensures the needs of train users and other stakeholders are fully understood and implemented throughout the entire lifecycle of train design, manufacturing, and maintenance. Peng Qibao et al. [3], based on MBSE methodology and the characteristics of manned space engineering, proposed a method for requirements analysis in manned space projects. Xu Zihe [4], relying on the Zhejiang University MBSE platform, developed a demand modeling and tracking system for complex products, establishing a data structure for requirement relationships. However, there is scant research on the analysis of requirements for individual high-speed train systems.

In response to traditional documentation-based requirement engineering methods being unable to meet the needs of current complex systems, this paper studies the requirements analysis and verification of the TCMS. Starting with stakeholders and guided by their requirements, the paper progressively confirms the functional requirements of the TCMS, analyzing, capturing, tracing, and ultimately verifying these requirements.

2 The Construction of the Requirement Model

The construction of a requirements model is an ongoing process of optimization and iteration, encompassing crucial steps such as stakeholder analysis and modeling, definition of requirements attributes, decomposition of requirements, and traceability modeling. The essence of this process lies in clarifying the specific needs of the target system, laying a solid foundation for the development work. The quality of the requirements has a decisive impact on the final quality of the product, making the establishment of a requirements model an essential part of system development. This paper employs the M-Design modeling tool to build models related to the requirements of the TCMS.

2.1 Stakeholder Analysis

By contemplating which stakeholders interact with, depend on, or influence the services provided by the high-speed train set's TCMS, its technical and non-technical components, business processes, and technical functions, one can identify the stakeholders involved during different lifecycle stages of the TCMS. After such contemplation, it is essential to review if any stakeholders have been overlooked.

The process of stakeholder identification consists of three steps: defining the target system, defining the lifecycle of the target system, and identifying and defining scenarios throughout the entire lifecycle of the target system. This paper conducts a detailed analysis of the stakeholders of the high-speed trainset's TCMS through literature review and team discussions. The identified stakeholders include train personnel, regulatory constraints, and the National Railways Group， this is shown in Figure 1.

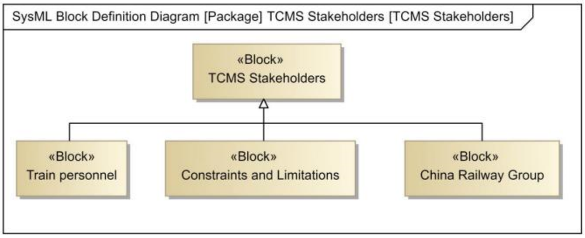

Fig. 1. TCMS Stakeholders.

2.2 Stakeholder Requirenment Capture

The capture of stakeholder requirements should commence from a macroscopic perspective, identifying the fundamental functionalities and performance specifications of the TCMS. The objective of requirement capture is to record the expressed needs of the interested parties in a consistent manner, ensuring accurate comprehension of these requirements. Utilizing methods such as individual interviews, brainstorming sessions, and scenario model reviews, the output of the requirement capture phase is a set of recorded requirements that are agreed upon by all stakeholders. These captured requirements serve as input for the requirement analysis process, which aims to document the requirements clearly and consistently alongside other pertinent information, establishing traceability to high-level requirements. The analyzed requirements are then used as input for requirement inspection and analysis by a requirements team, with the purpose of identifying any missing, conflicting, or incorrect requirements, ultimately leading to confirmed requirements that ensure the correctness and consistency of the captured and analyzed requirements.

#	id	△ Name	Text
1		⊟ TCMS Requirement	
2	1	⊞ R 1 L1-CR-1-A	China Railway Group requires TCMS should be set up on the EMU to control the EMU
15	2	⊞ R 2 L1-CR-2-A	China Railway Group requires that EMUs should be able to use TCMS to achieve information transmission and sharing

Fig. 2. Stakeholder requirenment.

With the China Railways Group as the primary stakeholder, a requirements model for the EMU (Electric Multiple Unit) train TCMS is established through discussions with experts in the field of EMUs. This will encompass the functionalities of control, communication, monitoring, and diagnostics proposed by the stakeholders for the TCMS (Train Control and Monitoring System). The Level 1 requirements for the EMU TCMS stakeholders are divided into four categories as outlined in Figure 2.

2.3 System Requirements Attribute Definition

This text provides a comprehensive description of the system requirements for the TCMS, including its necessary functionalities, performance, reliability, and safety. It encompasses an overview of the system's essential functional needs, non-functional requirements (such as performance criteria, safety standards, and reliability), constraints (like technological limitations and cost considerations), and other pertinent specifications. This aids in delineating the project's objectives and scope, offering guidance for subsequent detailed design and development phases. Initially, we approach from the vantage point of top-level design requirements and mission scenario planning, engaging with stakeholders through a model of the high-speed train environment to enhance the consistency of demand understanding. By adopting a scenario-oriented approach, we conduct a needs analysis for the TCMS, unearthing user requirements. We articulate the expectations of stakeholders concerning the high-speed train from their perspective. Functional analysis primarily involves examining the functionalities and performance that the TCMS should possess from the system's viewpoint, detailing the requirements for the high-speed train to fulfill stakeholder demands. Following an incisive dissection of stakeholder needs, the paper concludes with the identification of the functions the TCMS should have, illustrated as shown in Figure 3. These include: communication, diagnostic, control, and monitoring capabilities. The following text will analyze these four major functions in terms of system requirements.

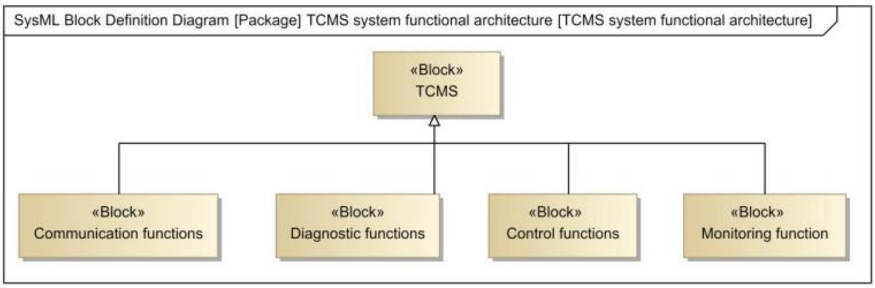

Fig. 3. TCMS system functional architecture.

The definition of requirement attributes is an important aspect in requirement management, and multiple types of requirement attributes can make the requirements more complete and able to display various information about the requirements. Currently, SysML language defines nine different types of requirement constructs, in order to support the modeling of requirements for the control system of EMU train network. Through the extension mechanism of SysML language, on the basis of SysML language, the following types of requirement constructs are defined: user requirements, product requirements, functional requirements, performance requirements, business requirements, interface requirements, standard specifications requirements, safety and reliability requirements, and other requirements. In addition, the versions, tiers, and stakeholder attributes are added, representing versions, levels, and stakeholders associated with the requirements, as shown in Figure 4 below.

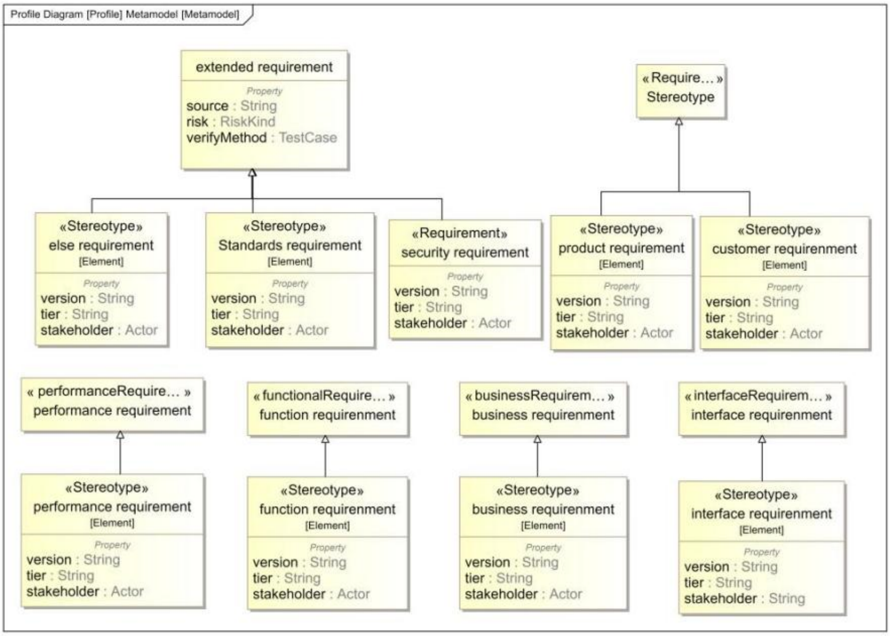

Fig. 4. Requirement Stereotype.

Upon the establishment of the high-speed TCMS's requirements architecture type, define the attribute types. Table 1 displays the names of the requirement attributes, the definitions of the attributes, and the content of the filled values.

Table 1. Requirement attributes.

The name of the property	description	value
Text	Actual system requirements	Requirement text description
Stakeholder	Stakeholders and related groups associated with that requirement	Name of the stakeholder
Versions	The latest version of the requirement change	A, B, C
Name	A unique code for a requirement, which contains information about the requirement	Encoded text

Satisfied	Indicates that the requirement is met by a component or part	The name of the assembly or part
Refined	Indicates that the requirement has been refined into a use case or feature	The name of the use case or feature
AppliedStereotype	The type of requirement to which the requirement belongs, which was used in the early management taxonomy	Customer , product , functional , performance , interface , etc
Tier	The level at which the requirement is located	L1, L2, L3, L4

2.4 System Requirements Capture

System requirement capture involves a comprehensive and profound analysis of the needs of the TCMS. During the capture process, it is initially necessary to identify and recognize all relevant stakeholders, such as the National Rail Group, related to the motor train unit, and engage in effective communication and cooperation with them. Through interaction with stakeholders, crucial insights into the system's requirements, expectations, and constraints can be obtained. At this stage, information is gathered, and key system requirements are preliminarily defined and understood, with further refinement and analysis of the captured requirements. This includes identifying and capturing functional requirements, non-functional requirements, constraints, system maintainability, safety, standardization, and regulation. For instance, the TCMS should possess robust fault monitoring and diagnostic capabilities and self-control abilities to minimize operational losses due to system failures. These requirements are then classified and prioritized. The goal of requirement analysis is to ensure consistency, completeness, traceability, and verifiability in the later stages of requirements[5].

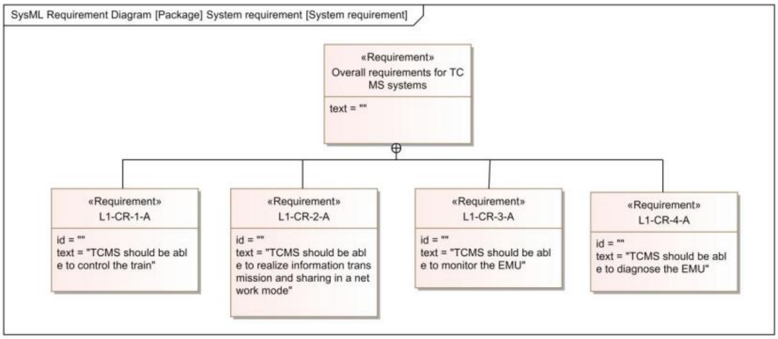

Fig. 5. TCMS system requirements

Within the process of capturing requirements for the TCMS, it is essential to comprehensively consider a variety of functional demands such as monitoring and diagnostics. This must be done in tandem with the user experience and technological advancements to ensure that the defined requirements are both exhaustive and precise, thereby laying a robust foundation for subsequent system optimization and iterations.

This text is guided by the needs of stakeholders and delves into analysing those needs, progressively transforming them into functional requirements for the TCMS. As demonstrated in Figure 5, the functional requirements L1 layer for the TCMS respectively are: train control, train monitoring, train diagnostics, and the ability for the TCMS to facilitate train communication.

2.5 System Requirements Decomposition

The zenith of the requirements analysis phase is the determination of inputs for the system engineering, with this text conducting a requirements analysis based on the communication, control, monitoring, and diagnostic functions achieved during the train's operational process. At this juncture, we ought to delve into the minutiae of each function, transforming scattered, textual user requirements into systematic needs, creating a requirements model, exerting unified management and storage over system requirements, and establishing a use case model post thorough requirement comprehension, all to propel functional analysis. This ensures that the system design caters to the core demands of efficient and secure operation.

As delineated in Figure 6, a detailed analysis of the L1 control functional requirements of the TCMS yields three L2 sub-requirements, which respectively comprise: the TCMS should be capable of actualizing two modes of control vehicle mode product requirements; as stakeholders of the TCMS, namely drivers and mechanics, they should be able to control dynamic vehicle functions through the system; and the TCMS should be able to manage the dynamic vehicle group or a specific power unit product requirement.

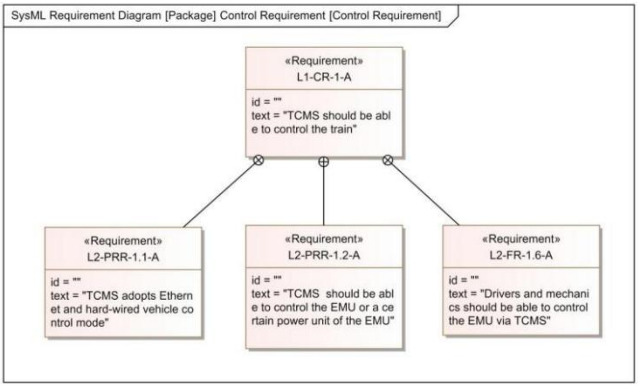

Fig. 6. Control requirements decomposition

A meticulous analysis of the communication functional necessities for the TCMS has yielded four L2 sub-requirements, as illustrated in Figure 7 below. These include: The TCMS should be capable of transmitting dynamic vehicle operation information, equipment status, and fault information; it should possess both wired and wireless transmission interfaces; it should ensure reliable and secure train-level and vehicle-level communication; and it should utilize a two-tier communication topology structure. Furthermore, a detailed examination of the requirements for the two-tier communication topology products has resulted in four L3 sub-requirements.

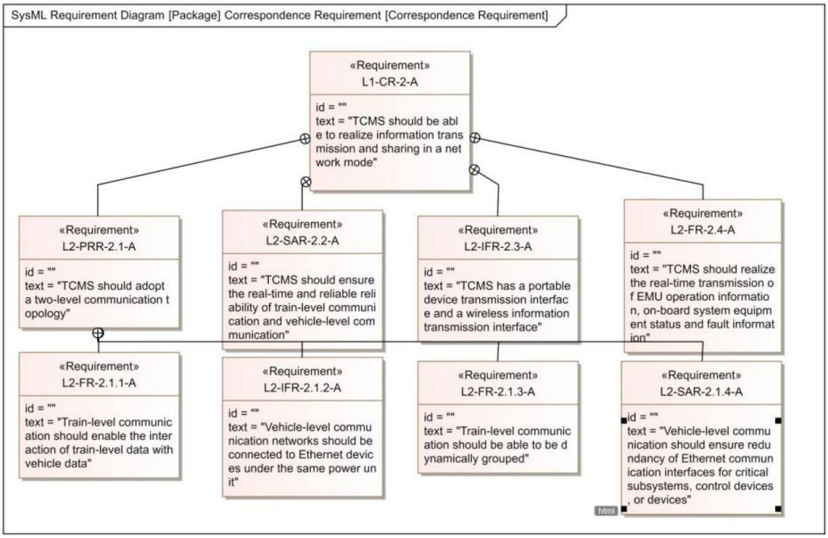

Fig. 7. Communication requirements decomposition

A thorough examination of the functionality required for train monitoring within the context of the TCMS has yielded three L2 sub-requirements, as depicted in figure 8 below. These comprise the necessity for the network control system's display interface to adhere to a unified standard for train display interface design, the requirement that the TCMS should be capable of presenting the complete operational status of the vehicle to both the driver and the mechanic, and the stipulation that the TCMS must be able to monitor the functional requirements of the power unit or the multiple units trainset.

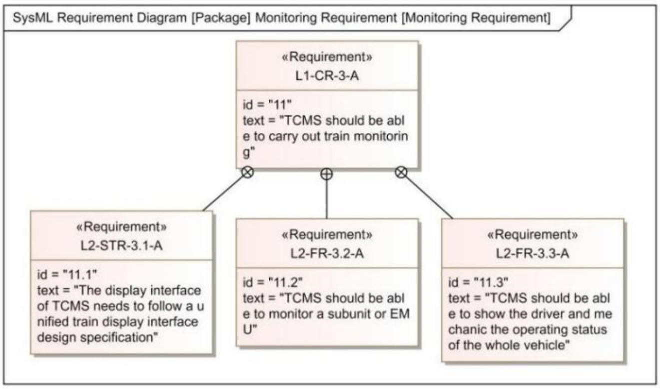

Fig. 8. Monitor requirements decomposition

A comprehensive analysis of the functional requirements for train monitoring within the TCMS yields eight L2 sub-requirements, as depicted in Figure 9. These encompass: adherence to a unified train diagnostic system fault code standard for TCMS fault codes, a demand for processing post-diagnostic fault data by the TCMS, a mandate for the TCMS to diagnose either the power unit or the entire trainset, a requirement for diagnostic capabilities extending to train-level communication, vehicle-level communication, and equipment status within the TCMS, a need for the TCMS to support effective maintenance and repairs for train personnel (drivers, mechanics) and maintenance staff during operation, maintenance, and repair periods, a standardized requirement for the TCMS to confirm, assess, report, and provide operational guidance for the majority of potential faults in all operating modes, including impacts on other systems, a stipulation that diagnostic information provided by the TCMS be accessible to maintenance personnel, along with necessary software tools, and a product requirement for the TCMS to offer methodological support for maintenance.

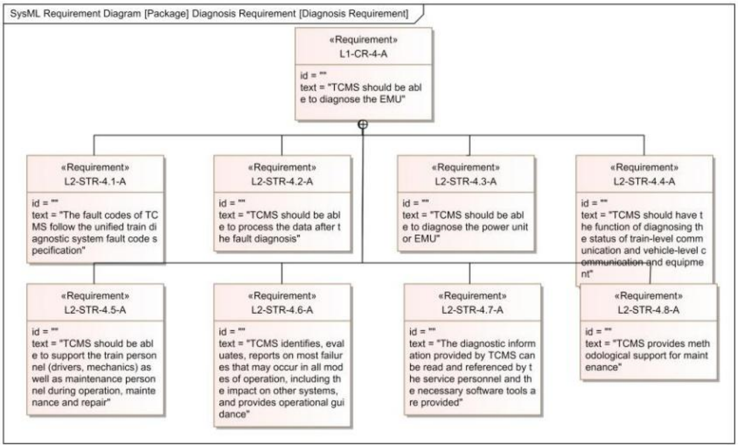

Fig. 9. Diagnostic requirements decomposition

2.6 Requirements Traceability

Throughout the system engineering process, requirements are subject to change. Requirement allocation traceability facilitates the identification of the impact of these changes on other parts of the system and ensures timely updates to the corresponding design and documentation, thereby maintaining system integrity and consistency. The clear relationship between system requirements and components aids in validation and verification processes, as well as meeting regulatory and standardization requirements. By allocating TCMS requirements, one can ensure that system needs are effectively transformed into specific tasks and functions for each component, enhancing the manageability and traceability of the system's design, development, and integration. Furthermore, requirement allocation supports modular and parallel development, accelerating progress and enhancing efficiency.

This text deconstructs the functionality of the TCMS, assigning fundamental functions to corresponding requirements and establishing their relationship through satisfaction links, thus constructing a requirement-function traceability matrix model as depicted in figure 10 below.

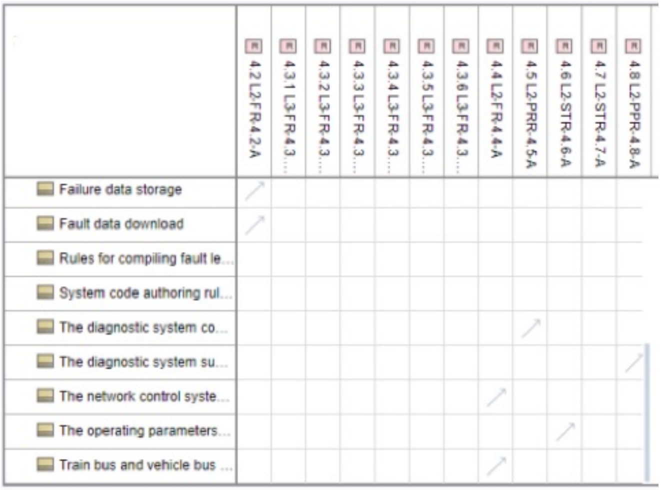

Fig. 10. Traceability of requirements and functions

Figure 11 illustrates that, taking the requirement that "the TCMS should be able to control the train" as an example, through the analysis of the operating scenario, the corresponding scenario use case diagram is established, the scenario use case is refined, and the relationship between the requirements and the use case is traced step by step. The refined relationship associates the use case with the requirements, ensuring that there is no omission in the traceability between the requirements and the use case.

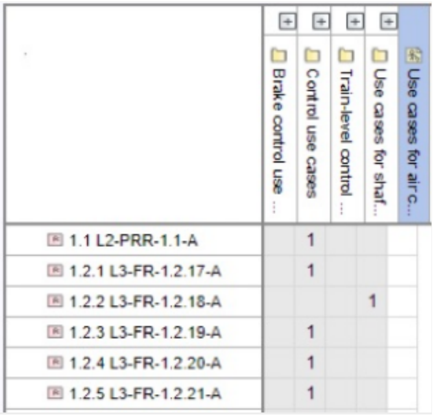

Fig. 11. Requirements Use Case Traceability

3 Requirements Validation

Verification of functional requirements is the process that ensures the system's needs fulfill the anticipated functions. From a black-box perspective, it aims to guarantee that the requirements proposed by stakeholders are met and that these can be traced back to corresponding functionalities. A grey-box analysis considers the logical relationships between systems to satisfy the product's own needs. From a white-box viewpoint, it is the physical relationships between individual components that make up each system that meet the needs of those systems[6]. Taking the requirement "TCMS can control door unit" as an example, this paper refines functional requirements through use cases and scenarios, allowing for precise descriptions of needs. Furthermore, from a white-box perspective, it establishes the interactions between systems. Ultimately, by setting up UI interface configuration driving logic control simulation tests, we can ensure that requirements are satisfactorily achieved.

Primarily, by dissecting the system's behavior, the target system's use case scenarios are depicted as illustrated in Figure 12. Subsequently, the functions of the target system and its interacting systems are determined, ultimately delineating the connection between the target system and its interactive systems, as well as the transmission of information flow amongst these relationships.

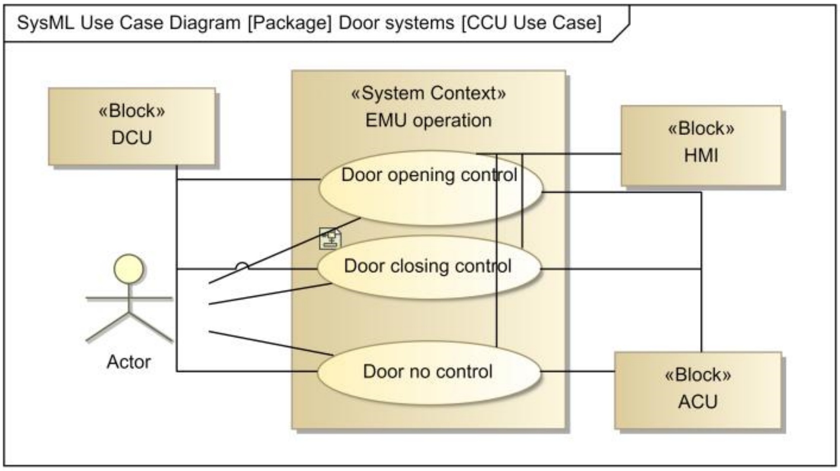

Fig. 12. Control Use Case Analysis

In accordance with the functional requirements of the TCMS, an analysis was conducted on the use case scenarios for controlling the operation of train doors. This resulted in a structural decomposition model of the high-speed train set, as depicted in Figure 13, which illustrates the simulation object for door control. The architecture involved in achieving door control functionality encompasses HMI (Human-Machine Interface), CCU (Central Control Unit), and DCU (Door Control Unit).

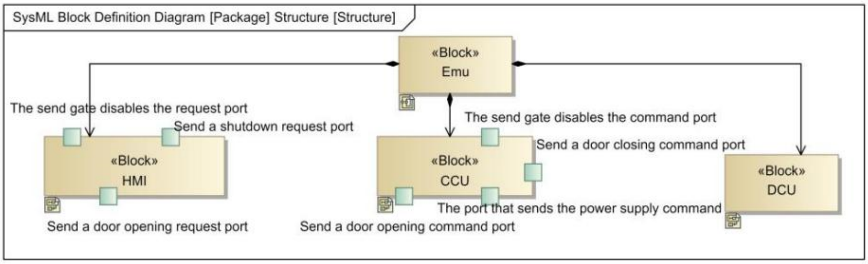

Fig. 13. Simulate the exploded view of the EMU structure for door control

Upon defining the gate simulation components and considering each component as a black box, it is necessary to clarify the signal flow between the components. As shown in figure 14 below, if the operator manipulates the buttons on the control panel, the control panel sends request signals to the CCU through the open door request port, close door request port, and door disable request port. The CCU then transmits command signals to the DCU through the open door command port, close door command port, and door disable command port.

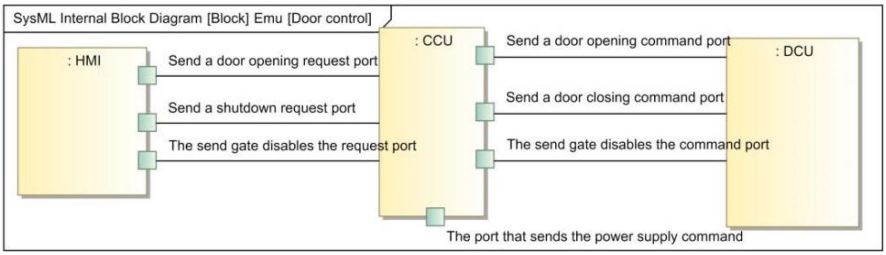

Fig. 14. Information exchange between systems

As depicted in Figure 15, a detailed specification has been provided for the TCMS's regulation of door activities, offering a more precise portrayal of system requirements. Dissecting the overarching needs of the TCMS into finer system behaviors facilitates the identification of functional blocks necessary for realizing functionalities, that is, logical subsystems. Capturing these logical subsystems clarifies the responsibilities each one bears. Furthermore, the functional flow model among the components is allocated to corresponding swimlanes of the logical subsystems. Through the establishment of swimlane diagrams, the functional blocks executed by each system structure and their logical relationships during the execution process of the door control function are clearly defined[7], along with logical simulation to ensure the veracity of logic and the fulfillment of functions.

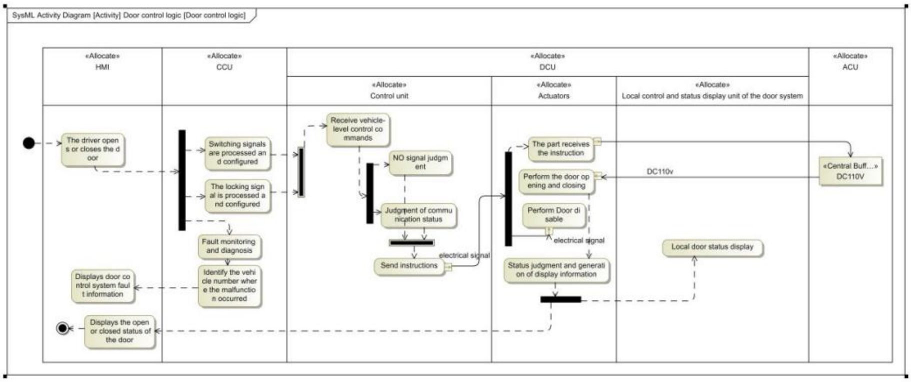

Fig. 15. Door control logic

The present text elucidates a simulation experiment on the logic control of train door networks through the modeling tool, CSM, using the operation of door opening as an exemplar. It affords operators a UI (User Interface) for interaction. As depicted in Figure 16, the configuration panel encompasses an "Open" button setting. By engaging this button, operators can transmit door-opening commands to the system, which will then execute the corresponding actions and relay the door status back to the UI, thereby facilitating the management of the TCMS.

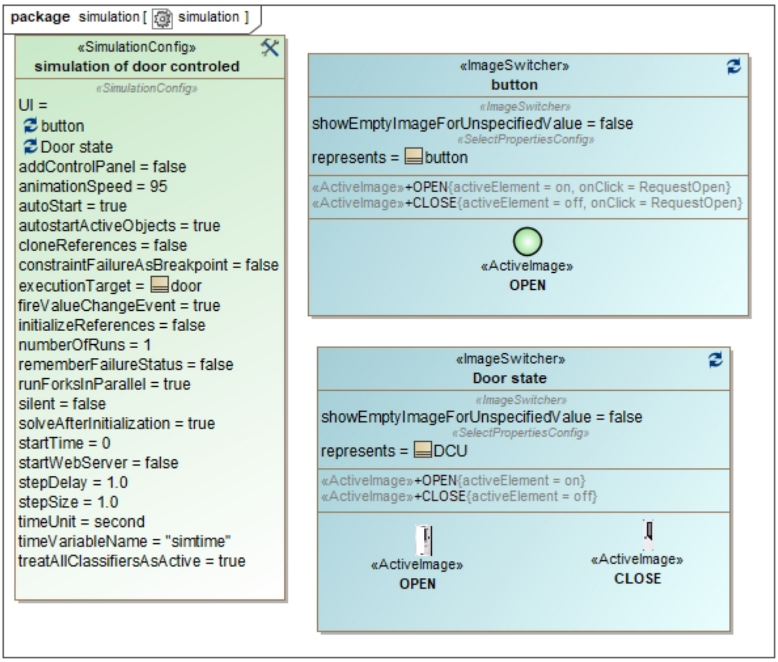

Fig. 16. Door Control Simulation Configuration Panel

The internal states of each system are depicted using a state machine, which also facilitates the analysis of activities, delineating the behavioral actions under varying states. The internal behaviors are designed according to the functionalities of each system, with triggering information, signals, and commands being exchanged through transmission. Figure 17 below illustrates the state representation of each system: upon the operator pressing the button, it receives the "RequestOpen" signal and transmits an "Open" signal through the "request port." Subsequently, the CCU receives the "Open" signal and dispatches an "Open command" to the DCU via the "command port."

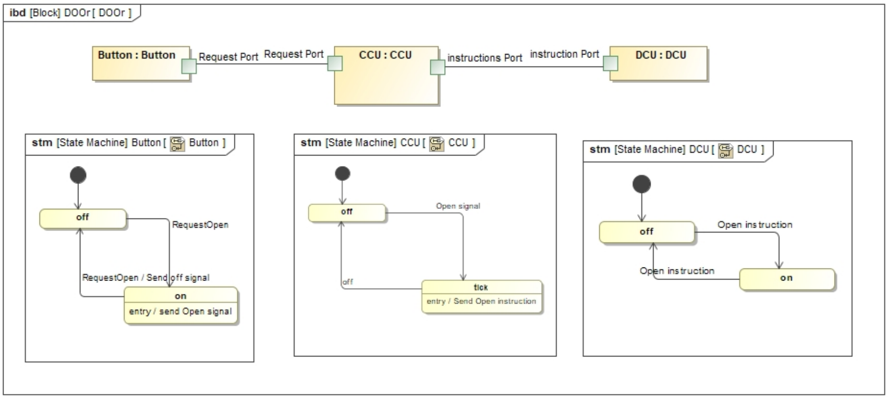

Fig. 17. Transition of the state of each system

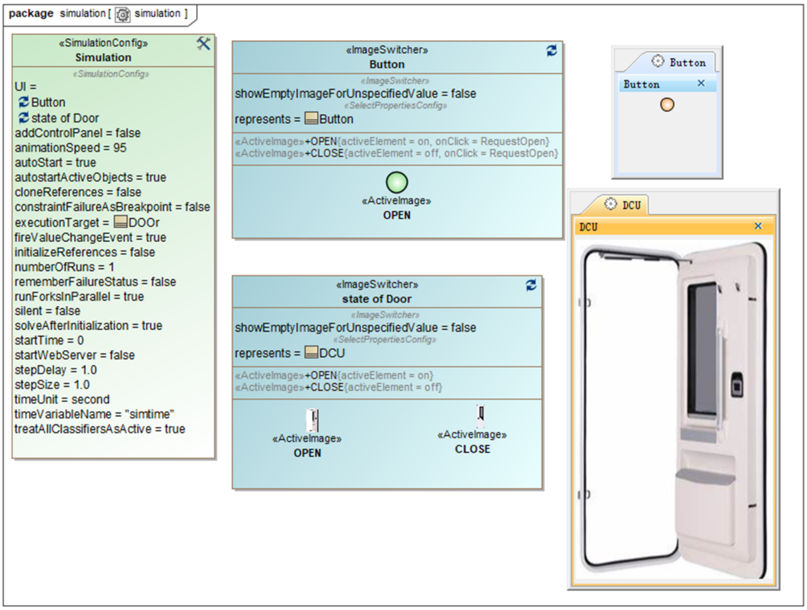

Fig. 18. The simulation model changes when the door is opened

In response to external system triggers, the triggerIn response to external system triggers, the trigger the construction of a simulation panel The design model undergoes a joint simulation via simulation configuration, thereby completing the verification of requirements. As depicted in figure 18, at this juncture, the car door transitions from the "Close" state to the "Open" state, and this status is presented to the operator through the UI interface.

4 Conclusion

During the TCMS system requirements analysis process, this During the TCMS system requirements analysis process, this SE concept, guided by user combined with the logic flow of the TCMS control door system of the multiple unit trainset, a logical simulation model is constructed, which animatedly presents the door control process of the multiple unit trainset, thereby ensuring that requirements are metIt， has a positive role in promoting the level of EMU technical management[8].

Acknowledgments

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References

1. Ruirui Chen, Chun-Hsien Chen, Yusheng Liu, Xiaoping Ye, Ontology-based requirement verification for complex systems, Advanced Engineering Informatics, Volume 46, 2020, 101148, ISSN 1474-0346.
2. Wang Baomin, Liang Yuzhe, Li Zhaoxing, et al. A Method for Demand Management of High-Speed Train Units Based on MBSE. Journal of Systems Engineering, 2023, 38(02):204-212+234. DOI: 10.13383/j.cnki.jse.2023.02.007.
3. Peng Qi Bo, Zhang Hai Lian. "Model-based Requirements Analysis Method for Manned Space Engineering". Systems Engineering and Electronics, 2023, 45(11): 3532-3543.
4. Xu Zihe. Research and Development of a Complex Product Requirements Modeling and Tracking System for MBSE. Zhejiang University, 2017.
5. Huang Tingli, Wang Baomin, Wang Haifang, et al. "Design and Modeling Methodologies for the IPIS System in Metro Trains." Journal of Graphic Studies: 1-10 [2024-04-22].
6. Guo Yuliang, Zhu Dongwei, Zhang Li, et al. Investigation into the Design of Railway Vehicle Door Systems Based on MBSE. Railway Vehicles, 2023, 61(05):81-87.
7. Wang Baomin, Chen Bo, Zhang Shicong, et al. An SysML-Based Simulation Study on the Control Logic of EMU Pantographs. Railway Locomotive Vehicles, 2020, 40(06): 11-18+27.
8. Wang Baomin, Chen Bo, Zhang Shicong. Research method and application of EMU vehicle logic based on MBSE. China Railway Science, 2021, 42(06): 143-151.