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RESEARCH ARTICLE

Chunfang LU, Yongjie PAN, Chaoxun CAI

Reliability guarantee framework for the Sichuan–Tibet Railway

Abstract The Sichuan–Tibet Railway is facing extraordinary challenges in terms of construction, operation, and maintenance because of its extremely complicated natural environment and geological conditions. Consequently, countermeasures are necessary and urgent to ensure its safety and reliability in the whole life cycle. This study proposes a novel reliability framework to guarantee the ideal operation state of the Sichuan–Tibet Railway. Reliability application in many fields are summarized, including military equipment, rail locomotive, and railway engineering. Given the fact that the Sichuan–Tibet Railway is a complex giant system, Nine-Connotation was summarized (i.e., safety, inherent reliability, testability, maintainability, supportability, environmental adaptability, predictability, resilience, and durability) under the goal of optimizing the operational efficiency. On the basis of the concept of the Nine-Connotation and the understanding of reliability transmission mechanism, the framework of reliability for the Sichuan–Tibet Railway was established, which can facilitate a comprehensive and real-time evaluation of all situations with a clear hierarchy. The proposed framework is composed of a resilience management system, an integrated technology system, and a dynamic reliability assessment system. The pathway for its application on railway construction was developed in this study. The proposed framework can assist in well-informed decisions for the construction, as well as the operation of the Sichuan–Tibet Railway. On the basis of a top–down design concept for the first time, this study emphasizes the railway's availability and validity to complete the assigned tasks as a whole, that is, operational efficiency. It also shows the reliability transmission and control mechanism of the railway's giant complex system, innovating and establishing the management principle of great safety and great reliability over the life cycle.

Keywords Sichuan–Tibet Railway, operational efficiency, reliability guarantee, Nine-Connotation, implementation pathway

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Chunfang LU
China Academy of Railway Sciences Corporation Limited, Beijing 100081, China

Yongjie PAN (✉), Chaoxun CAI
China Academy of Railway Sciences Corporation Limited, Beijing 100081, China; State Key Laboratory for Track Technology of High-speed Railway, Beijing 100081, China
E-mail: 18810622516@163.com

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1 Background

The Sichuan–Tibet Railway connects Chengdu and Lhasa, with a total length of 1567 km, passing through Ya'an, Kangding, Yajiang, Batang, Changdu, Bomi, Linzhi, and Shannan from east to west. The construction is divided into three sections, i.e., Chengdu to Ya'an, Ya'an to Linzhi, and Linzhi to Lhasa. The first section between Chengdu and Ya'an has been put into operation since December 2018. The construction of the section between Linzhi and Lhasa began in December 2014, which is about to start operation in 2021.The passenger rails are expected to run at a speed of 200 km/h (Lu and Cai, 2019).

The construction of the Sichuan–Tibet Railway overcomes the greatest risks in railway construction in the world. The first one is the harsh natural environment. The railway lines cross seven deep rivers and eight high mountains, which are potential earthquake sources and environmentally sensitive zones. Extreme weather and climate changes, such as gale, rainstorm, snowstorm, and strong convection, occur frequently. The maximum diurnal temperature variation is up to 35°C. In the active fault zone and intrusion area rock band, the soil temperature and rock temperature can be as high as 90°C. Moreover, the high-intensity ultraviolet combined with thin air in the high-altitude area makes the construction even more difficult. In addition, the Sichuan–Tibet Railway involves many complex projects, including large, complicated bridge construction projects and structures and ultra-long tunnels that make the construction even more challenging. The railway is close to the border, facing the risk challenge of multi-culture and multi-society barriers, which makes the construction more difficult. Furthermore, the construction period is over 10 years. Such a long period brings more unpredicted risks, which brings more uncertainty to the management of workers, equipment, and environment. In conclusion, the Sichuan–Tibet Railway is the most challenging project in the field of railway engineering thus far.

The investigation of the reliability strategy and safety management in the aspect of the entire life cycle of the Sichuan–Tibet Railway is urgently needed to guarantee high-quality design and construction.

2 Current situation of reliability application

The general definition of reliability for a structure is “its ability to fulfill the design purpose for some specified design lifetime, which is often understood to equal the probability that a structure will not fail to perform its intended function” (Nowak and Collins, 2005). To improve the quality of complex giant systems in China, relevant studies have been conducted on the meanings and applications of reliability. Qin and Lu (2011) pointed out that reliability evolves from engineering problems, theory, and technology to reliability engineering subjects. Maintainability, supportability, and testability have been successively separated from reliability during the evolution, presenting the hierarchical progressive mode of engineering. On the basis of the narrow sense of reliability, availability, maintainability, and safety (RAMS), Zhang (2017) argued that supportability can be regarded as the general RAMS. In that study, the profound connotation of the general RAMS was interpreted, and its influence and significance in the engineering consulting industry were analyzed. Kang and Wang (2005) and Kang (2012) illustrated the concept and definition of reliability system engineering and preliminarily established a theoretical and technical framework. They pointed out that the ultimate goal of equipment management is quality management of the entire system covering every stage. Huang (2013) designed a reliability framework for a natural gas network by considering the reliability of product safety and gas supply safety. Cheng and Han (2012) proposed the concept of engineering management systems, in which the optimal goal of the whole project is achieved through management activities in the project life cycle. Ding (2014) claimed that the quality characteristics of construction projects are epitomized in safety, applicability, durability, reliability, economy, and coordination with the environment. Hidirov and Guler (2019) developed a model framework including four stages and applied the reliability, availability, and maintainability analyses to the railway infrastructure management. Zhu (2021) proposed a new diagram of categorizing system-level failures and further incorporated a diagram into the development of complex system reliability framework.

The aforementioned studies indicate that reliability is a generalized philosophy that can be used to analyze various types of system, such as infrastructures and equipment. Reliability-based philosophies are suitable for decomposing complex systems from two dimensions, namely, life cycle phases and subsystems. To establish a reliability guarantee framework for the Sichuan–Tibet Railway, the application of reliability in military equipment, track locomotive, and railway engineering are described in detail, and the outcomes can be references in the analysis of the Sichuan–Tibet Railway.

2.1 Military equipment

To solve the imperative reliability problems of missiles and military electronic equipment during World War II, the US Army established the Military Electronic Equipment Reliability Advisory Group in 1952 to formulate reliability research and development plans. In 1957, the Reliability of Military Electronic Equipment report was issued, which proposed the methods and procedures of reliability design analysis and test evaluation standards of military electronic equipment. It became a cornerstone document for reliability engineering, indicating that reliability engineering has become an independent discipline in the field of engineering, maintenance, and guarantee (Kang, 2012). The former reliability standard of military equipment MIL (Sun, 2012) can effectively avoid the potential risks in the process of equipment development and greatly improve the readiness rate of the equipment and mission success.

Referring to the standard of the US Army, reliability studies on Chinese militaries have focused on fixing the lack of a common goal in quality design, such that integration can be achieved in universal quality characteristics, between universal and specific qualities and between technology and management. The ideal goal of system efficiency is “available”, “credible”, and “possible (to win)”, in which the former two are determined by general quality characteristics.

General quality characteristics include reliability, maintainability, testability, safety, supportability, and environmental adaptability — the Six Characteristics in Military Equipment. These characteristics are the important components of system efficiency, which respectively correspond to “General requirements for materiel reliability program” (GJB 450 A-2004), “General requirements for materiel maintainability program” (GJB 368 B-2009), “General requirements for materiel testability program”

(GJB 2547 A-2012), "General requirements for materiel safety program" (GJB 900 A-2012), "General requirements for materiel integrated logistics support" (GJB 3872-1999), and "General requirements for materiel environmental engineering" (GJB 4239-2001).

2.2 Track locomotive

In 2008, the standard of Railway Applications — Specification and Demonstration of Reliability, Availability, Maintainability, and Safety (RAMS) (IEC 62278:2002) was introduced to China, which was translated as the national standard GB/T 21562-2008. Part 2 (Guide to the application for safety) and Part 3 (Guide to the application for rolling stock RAM) in GB/T 21562, released in 2015, were issued by the National Railway Administration of China.

RAMS management is mainly applied in the vehicles in urban rail transit and various advanced electromechanical equipment. As the theory is based on the idea of integral theory and system theory, RAMS is widely adopted throughout the whole life cycle of rail transits. It consists of the following processes: The initial concept of the system; system definition; application conditions; risk analysis; feasibility analysis of identifying and distributing the system demand; and design, manufacture, commissioning and formal operation, maintenance, and failure (Mahboob and Zio, 2018), as shown in Fig. 1. In Fig. 1, Nodes 1–6 on the left side correspond to the inherent characteristic formation of products, whereas Nodes 8–10 on the right side correspond to the verification stage of RAMS characteristics. Finally, the requirement of service is confirmed in the whole system.

To satisfy the safety and availability in service, it must meet the requirement of reliability and maintainability, as well as the ability to operate and repair in daily activities under an appropriate system operating condition (Mahboob and Zio, 2018). Safety and availability are correlated, and the balance between them is critical for system reliability.

2.3 Railway engineering

Great attention has been paid to the research and application of reliability in railway engineering in China. The safety of railway structure can be divided into three levels based on the considerations listed in the Reliability Design Standard of Railway Structure (GB 50216-2019), which are the threat to people's life, the loss of economy, and the effect on society and environment. The Standard specifies that the reliability level should be determined according to the level of safety, failure mode, and economic factors. It also provides the principle of reliability assessment and the basic requirements of safety, durability, reliability, resilience, and environmental adaptability. Thus far, the limit state design specification for each subdiscipline is under development. Chen et al. (2006) proposed a reliability evaluation method based on accident tree analysis, which describes the logical relationship among the failures caused by the traction power supply system in an electrified railway. Yang (2011) conducted a systematical research on the evaluation of RAMS for a high-speed railway traction power supply system. By utilizing the Markov model, Chen et al. (2020a) developed a safety and reliability evaluation model of an autonomous computer system of an intelligent centralized traffic control in a high-speed railway. Although many efforts have been made on reliability studies by different subdisciplines of railway engineering, no consensus is achieved on the intrinsic implication of reliability. It lacks requirements of coordination and optimization in different subdisciplines. Few studies have focused on the reliability of the entire system because of the comprehensiveness and complexity of railway engineering. The evaluation index system of railway industry safety production proposed by Jia et al. (2015) involves

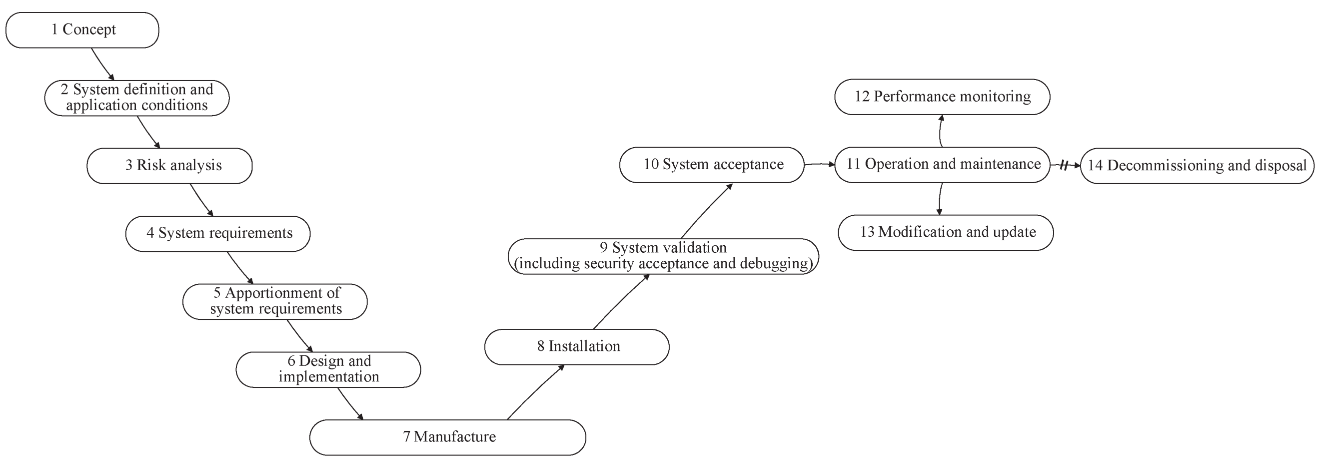

Fig. 1 RAMS life cycle management.

accident, injury, and death rates and availability of facilities and rolling stock, which are from post-events statistics and cannot play a positive guiding role from the beginning of the design process. Cheng et al. (2019) provided a preventive, opportunistic maintenance method to schedule the maintenance process of the catenary system of high-speed railways. Meng et al. (2020) defined the reliability of railway networks based on probability theory and constructed a reliability optimization model for a railway network to enhance the railway network with a limited investment. Gu and Li (2019) constructed a topological networked model to analyze the reliability of a high-speed railway network with respect to the destruction caused by different types of disaster. Feng et al. (2019) discussed the reliability of the railway transportation system from a practical transportation perspective.

The above analysis results only focus on some issues in the railway system. Taking the Sichuan–Tibet Railway as a whole, a reliability guarantee framework for the complex giant system must be developed urgently. The connotations of reliability guarantee are expanded and illustrated in this study. Furthermore, the mechanism of reliability transmission is fully investigated. The implementation methods of reliability guarantee are suggested for the construction period. The developed framework can effectively assess the system reliability in advance rather than after an event, which can greatly improve the reliability management of the Sichuan–Tibet Railway.

3 Connotation of reliability guarantee for a complex giant system

3.1 Operational efficiency

The complex giant system is an idea proposed by Qian (2005), which is characterized by the large size of the system, numerous elements or subsystems, and the complex relationships among one another. The components in the complex giant system are different, and their interaction cannot be identified. The performance of the entire system is nonlinearly affected by each component, such that the behavior of the system cannot be predicted analytically.

The Sichuan–Tibet Railway can be deconstructed into six subsystems, namely, civil engineering, locomotives, communication signals, traction power supply, operation and maintenance, and risk management (Lu, 2015). Each subsystem contains several components, including intervals, units, and modules. To analyze the reliability of the complex system, environmental condition and predetermined function should also be clarified. For the Sichuan–Tibet Railway, the environmental condition is extremely harsh, including large temperature difference and high-intensity ultraviolet radiation, combined with disasters excited by nature or humans, which leads to extremely high failure probabilities. Moreover, the function of the system is more important than fulfilling some specific functions. Therefore, the Sichuan–Tibet Railway is a typical complex giant system with multi-state functions, multi-state faults, and dynamic changes of various elements and parameters at any time. It is characterized by the development of human-oriented and deep integration of human and machine. On the basis of the long-term requirements of a stable and reliable operation, the goal of reliability guarantee is to optimize system efficiency to perform multiple tasks (i.e., available and reliable ability of the railway giant system to complete specified tasks, which is called operational efficiency).

Operational efficiency is goal-oriented based on top–down design methods. It is active in the whole life cycle of the complex giant system of the Sichuan–Tibet Railway, including the planning, design, construction, operation, and maintenance periods. Operational efficiency is embodied by the requirements and implementation of reliability, maintainability, and supportability. The concerned tasks in different periods and sublevels are different, such that the corresponding connotation of reliability is adjusted accordingly. The management of reliability guarantee is shown in Fig. 2.

3.2 Nine-Connotation

Referring to the existing studies of the Six Characteristics in military equipment and RAMS, the Nine-Connotation of reliability guarantee, namely, safety, inherent reliability, testability, maintainability, supportability, environmental adaptability, predictability, resilience, and durability, is proposed to meet intelligent construction and smart operation because of the combined effects of ambitious goals, long-term management, multiple risks, and harsh environment (Fig. 3).

The Nine-Connotation of the reliability guarantee for the Sichuan–Tibet Railway can be interpreted as follows.

Safety: It is the ability to maintain a certain condition over a period of time, without human injury or death, harmful effect on human health and environment, nor any damage of human body, equipment, or property. The concept of safety comes from accidents. For the complex giant system of the Sichuan–Tibet Railway, the probability of major accidents resulted from system failure or destruction must be reduced, as well as the consequences of the loss of personnel and property.

Inherent reliability: It is the inherent attribute of the Sichuan–Tibet Railway due to the nature of design and construction, that is, the reliability level under the predetermined ideal operational conditions. Inherent reliability is a quality in the time domain. With the increase of service life and the occurrence of uncertain events, the giant system is subject to a slow process of degradation. When the degradation accumulates to a

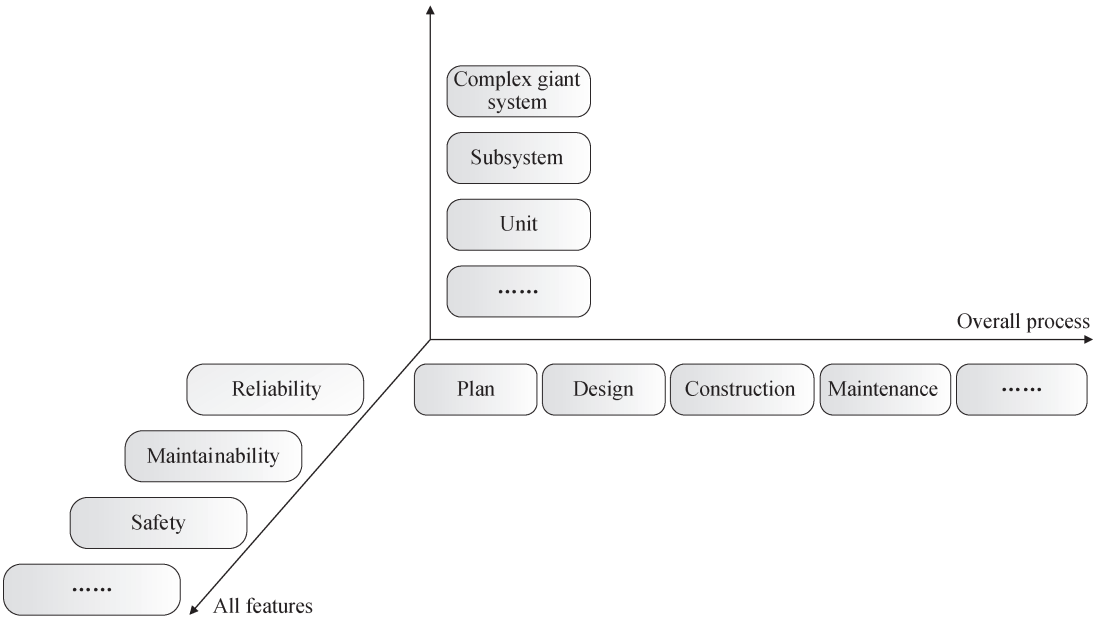

Fig. 2 Reliability guarantee management of the Sichuan–Tibet Railway.

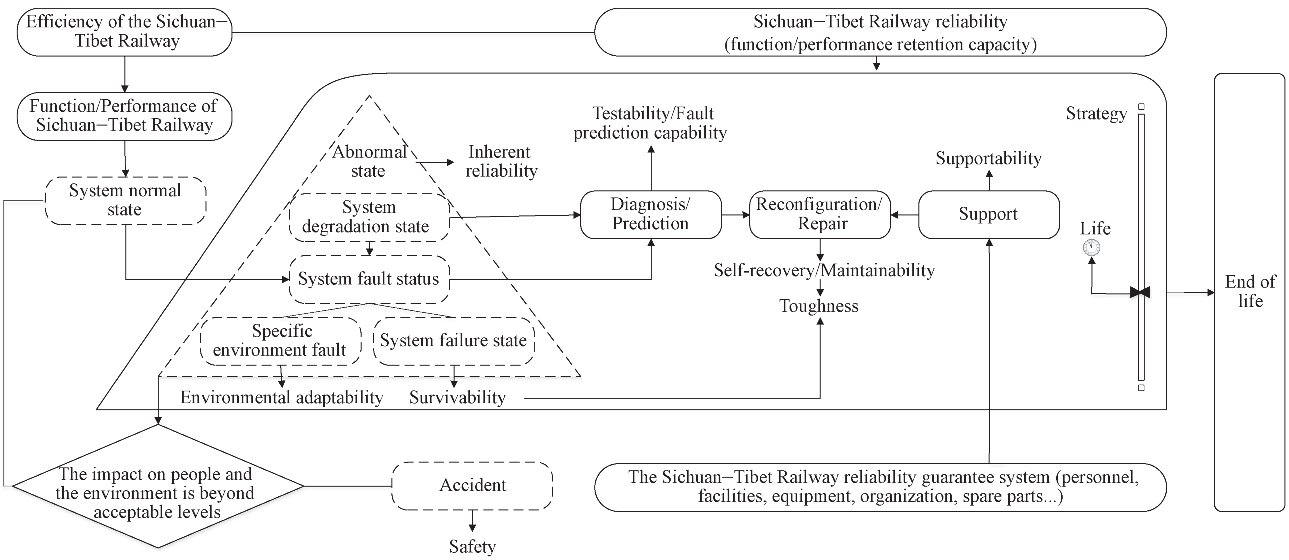

Fig. 3 Connotation of reliability guarantee in the life cycle of the Sichuan–Tibet Railway.

certain degree, the system may experience failure, including specific environmental failure, system failure, and accident. It is directly related to the prevention, stimulation, improvement, and evaluation of potential faults/defects. The seriousness and potential fault characteristics directly affect the demands of testability, maintainability, and supportability.

Testability: It is a characteristic of the Sichuan–Tibet Railway that it can timely and accurately identify its status (e.g., working, non-working, or performance degradation) and isolate the internal faults. It reflects the ability to identify, diagnose, and evaluate the working status.

Maintainability: It is the ability to maintain or restore the specific functions through maintenance, following specified procedures and methods under possible restriction and time-limit conditions.

Supportability: It indicates that the design and resources are sufficient in assisting the completion of a target function. The resources include human resources, technical data, equipment, supply guarantee, and facilities.

Environmental adaptability: It is an extension of the inherent reliability through which the expected function and performance can be realized and/or the ability to not be destroyed under various environmental effects in the life cycle. Environmental adaptability is important, given that the Sichuan–Tibet Railway may encounter unpredicted faults under extremely cold and plateau conditions.

Predictability: It is the ability to predict degradation. This characteristic is desired to predict the working status and tendency accurately and timely.

Resilience: It is the ability to resist failure and recover from destruction. It is a comprehensive measure of recovery performance and recovery time after a destruction. It is influenced by the destruction resistance, self-recovery, and maintainability of the system, as well as the supportability.

Durability: It is the desired life span. It emphasizes the span of time. Particularly, for a structure or component that is not repairable, the time of its first failure is its service life.

The Nine-Connotation illustrates the nine characteristics of reliability guarantee. These characteristics are different but interrelated. Safety is the most important characteristic, in which accidents and loss of lives and property should be avoided. Inherent reliability is the ability of functioning and minimizing the chance of failure. The requirement of quick maintenance is under the condition of timely testability. Environmental adaptability is required to overcome harsh environmental conditions. Durability is the ability to serve for a long time. Resilience indicates the capability to recover from destruction. Predictability is the concept of Prognostics Health Management (PHM) for fault diagnosis and health management. Supportability is the foundation of all the other characteristics. It constitutes the idea of great safety and reliability in a general sense.

Qian (2005) reported that "reliability is guaranteed by the design, production, and management". Therefore, the reliability of the Sichuan–Tibet Railway is influenced by the connotations and the corresponding technology and management during the implementation process, as shown in Fig. 4. On the one hand, it corresponds to the availability and credibility of the Nine-Connotation to ensure the function and performance of the system. On the other hand, it relates to the management and technology system, involving the specific implementation step in which the design and construction are most important.

3.3 Mechanism model of reliability guarantee

Nine-Connotation of the reliability guarantee for the Sichuan–Tibet Railway can be regarded as the nine characteristics under the scheme of Great Safety and Great Reliability. The objective is to optimize the operational efficiency to complete the given tasks. The efficiency E is a function of nine characteristics:

$$E = q\begin{pmatrix} k_1a_1, & k_2a_2, & k_3a_3, & k_4a_4, & k_5a_5, \\ k_6a_6, & k_7a_7, & k_8a_8, & k_9a_9, & \end{pmatrix} * C_\mathrm{R},$$

where k_1, ..., k_9 represent the connotation of inherent reliability (a_1), maintainability (a_2), testability (a_3), safety (a_4), supportability (a_5), durability (a_6), resilience (a_7), predictability (a_8), and environmental adaptability (a_9), respectively; $q(\cdot)$ is the availability and credibility of the Sichuan–Tibet Railway, which is a comprehensive function of the nine characteristics; and C_R is the inherent capacity of service (e.g., transportation) of the Sichuan–Tibet Railway.

Traditionally, in a typical optimization problem for construction, economic cost C is regarded as the objective of optimization design, and key parameter X is the independent variable. In view of the performance requirements, the optimization model is as follows:

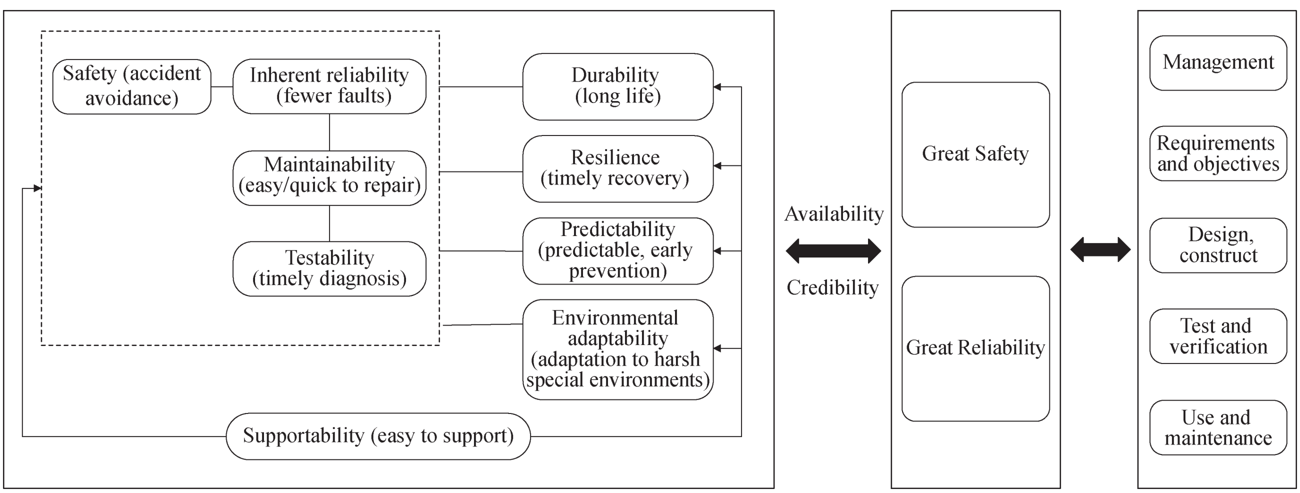

Fig. 4 None-Connotation of reliability guarantee for the Sichuan–Tibet Railway.

$$\text{Objective function: } \min(C_t)$$

$$\text{Constraints: } g_{a_i}(X) \geqslant g_{a_i}^*$$

$$\text{Independent variables: } \mathbf{X}$$

where $\mathbf{X}$ is the parameter vector in reliability design; C_t is the cost of construction; $g_{a_i}(X)$ is a function of connotation characteristic a_i, that is, the capability of X to fulfill a specific function; and $g_{a_i}^*$ refers to the requirement of design related to the connotation characteristic a_i. In the past, reliability guarantee does not have the whole nine characteristics, such that $i < 9$.

When the objective is efficiency, the optimization model is as follows:

$$\text{Independent variables: } \mathbf{X}$$

$$\text{Constraints: } C \ngtr C_d;$$

$$g_{a_j}L^* \leqslant g_{a_j}(X) \leqslant g_{a_j}U^* \quad (j = 1, 2, ..., 9)$$

$$\text{Objective function: } \max(E_d)$$

where C_d is the life cycle cost of the project; E_d is the operational efficiency; and $g_{a_j}L^*$ and $g_{a_j}U^*$ are the designed lower and upper limits of connotation characteristic a_j, respectively.

From construction targeted at the least cost to system design targeted at the best performance in the entire life cycle, the design and management strategy are fundamentally changed for the reliability guarantee for the Sichuan–Tibet Railway as follows.

(1) The goal changing from performance to efficiency reflects the goal of service value.

(2) Integrating life cycle cost in the function instead of construction cost indicates the comprehensive consideration of the system economy, which is an advancement in the transformation from “construction first and maintenance second” to “construction and maintenance both matter”.

(3) Efficiency is set as the goal, and safety is the fundamental requirement. In view of the life cycle cost, the concept of “Great Safety, Great Reliability” is strengthened, and the concept of the combination of being goal- and problem-oriented is highlighted. Scale-based expansion is changed into quality–benefit mode.

(4) The basis of maximizing efficiency is the integration of technology and management, which changes the original processing mode that seeks for the optimization of reliability guarantee based on the existing technology system and management system. It also promotes the personalized customization, collaborative development, and innovation promotion of the technology and management systems.

4 Development of reliability guarantee framework

On the basis of the Nine-Connotation of reliability, the activities of the entire life cycle management of the railway system must be sorted out, the reliability transmission mechanism must be analyzed at different levels of the giant system, and the closed-loop management process should be suggested to provide a foundation for the reliability guarantee framework.

4.1 Life cycle management

The establishment of reliability guarantee for the Sichuan–Tibet Railway runs through the whole life cycle of railway design, construction, operation, maintenance, and demolition. In view of the approach of the V model in RAMS, the stages of this project in the whole life cycle is presented in Fig. 5.

The Technical Specification for Risk Management of Railway Construction Projects (Q/CR 9006-2014) clarifies the key components for the risk management in construction, including feasibility study, preliminary design, construction drawings, objectives, workflow, and typical risk factors. The Sichuan–Tibet Railway encounters six major challenges, namely, the considerable difference in elevation, strong plate motion, frequent geological hazards, sensitive ecological environment, harsh environmental conditions, and weak infrastructure. Thus, its life cycle management involves risk assessment in a multi-aspect and multi-factor manner, which shows that the strategies of technology and management are iterative and risk-driven.

Demand allocation is to decompose the targeted efficiency to subsystems, units, and components. It exists in different steps of different tasks that decomposes the overall demand to each sublevel. Demand allocation is a decomposition process from the whole to the parts and from the upper level to the lower level repeatedly. Each task corresponds to a certain amount of reliability distributed from the system reliability. According to the allocation principle, specific plans are designed and implemented in the design, manufacturing, and construction phases. To achieve the plan, it should be checked frequently in accordance with strict specifications. In the period of operation and maintenance, performance monitoring, PHM, emergency rescue, and preventive maintenance should be considered.

4.2 Transmission mechanism of reliability guarantee

On the basis of the characteristics of the Sichuan–Tibet Railway, the transmission mechanism should be investigated from a global perspective. Function, performance, and reliability in different levels of interface and the

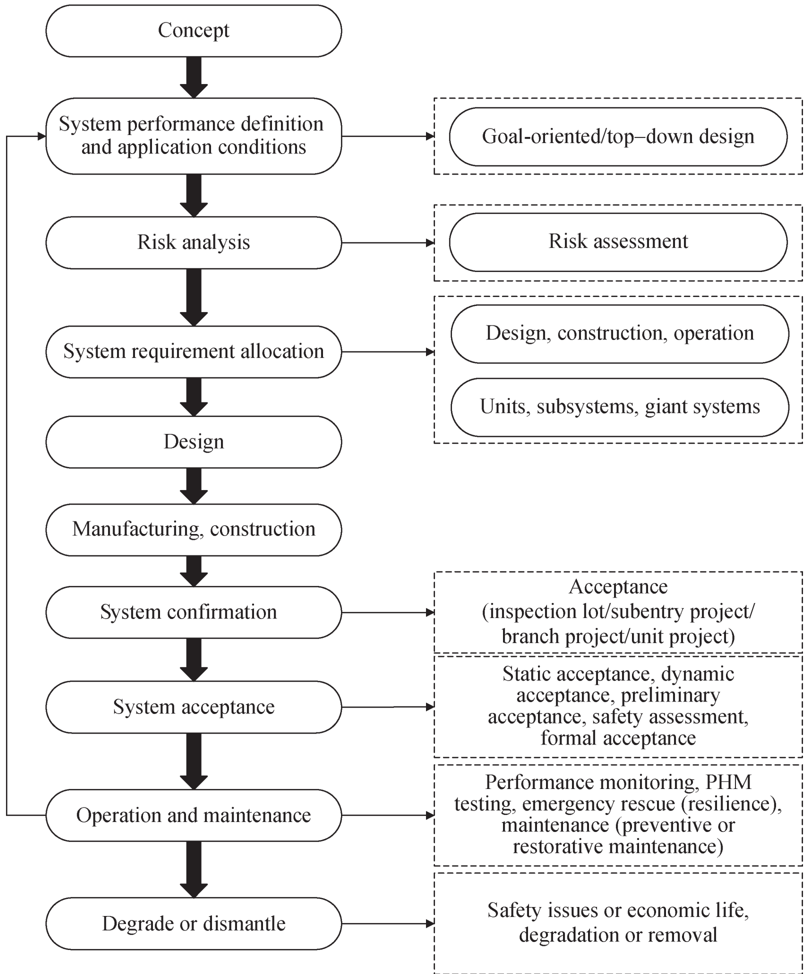

Fig. 5 Life cycle of the Sichuan–Tibet Railway.

information interaction between subsystems and units should be analyzed. In addition, systematic thinking — the integration of resources and humanistic care — is valuable in project management. For a better application in the Sichuan–Tibet Railway, the connotation of the plan–do–check–action (PDCA) cycle of the overall quality management must be redefined.

A preliminary transmission mechanism model is constructed based on the life cycle activities of the Sichuan–Tibet Railway, as shown in Fig. 6. The upper of the pyramid stands for the construction process, where the starting point represents the Nine-Connotation of reliability guarantee and efficiency goals. Each plane can be taken as specifc task or job, such as inspection lot; the general requirements of reliability allocation shall be undertaken as input conditions of reliability guarantee to be transferred to the next task. Then, subentry, branch, and unit projects can be accomplished through the same manner. The middle of the pyramid is on behalf of the final acceptance testing of the system to be used. The bottom of the pyramid represents the operational period, and the end point corresponds to the failure or disruption.

In the process of implementation, prior control and in-process control are important to avoid post control. Therefore, the virtual simulation of the assessment model is needed, which should cover all the tasks in the whole process. The simulation can digitally model the behavior of physical objects, assess and validate the tasks in advance, and optimize the strategy of technology and management timely. Finally, a two-mode verification combining virtual and reality is established. The simulation in the Sichuan–Tibet Railway is constructed based on the full understanding of the reliability engineering and the logical model of different levels. Moreover, it continuously interchanges and evaluates the information with the objects in the real world. The digital twin is formed, covering the phases of survey, design, construction, operation, and maintenance, as well as the giant system, the subsystem, and the unit level. The simulation is featured by self-learning and adaptive technology, which can deliver multi-dimensional information and physical objects synchronously. It assists the health condition awareness and dynamic decision optimization for the giant system.

In summary, the need for the reliability guarantee for the

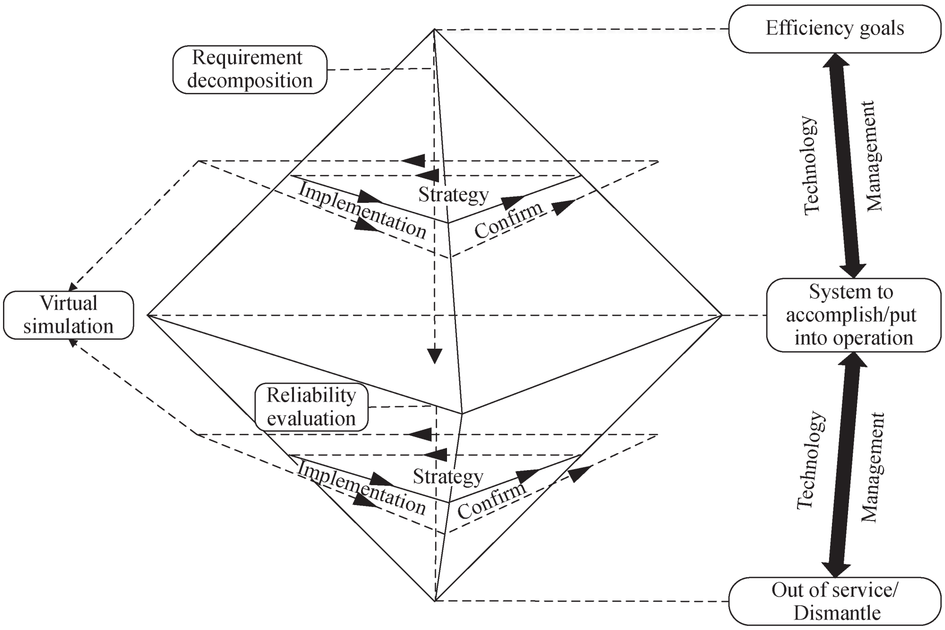

Fig. 6 Transmission model of the reliability guarantee for the Sichuan–Tibet Railway.

Sichuan–Tibet Railway comes from the demand of the society, economy, politics, and army, and then rise to the value driven of upper level. Under the goal of operational efficiency, with the assistance of technology, management, and safety strategies, risks can accurately be assessed and predicted in advance, such that a targeted implementation can be performed. The implementation is then validated immediately for further optimization. The aforementioned stages finally form a management system of “Demand–Destination–Strategy–Assessment–Do–Check” (DDSA + DC), which serves as the foundation of the reliability guarantee framework.

DDSA + DC management is a closed-loop process, which has the same idea as the confirmation and validation in the rail transit RAMS system shown in Fig. 7. The requirements in RAMS corresponds to the combination of Demand and Destination in DDSA + DC. The Strategy and Do in DDSA + DC are equivalent to the distribution in RAMS. The Check in DDSA + DC is equivalent to the confirmation and acceptance in RAMS. Finally, the Assessment in DDSA + DC corresponds to the validation in RAMS.

Examples of DDSA + DC application are the risk management of railway construction projects, the evaluation of the first part, and the construction of first trial sections.

4.3 Reliability guarantee framework

The reliability guarantee framework is presented in Fig. 8, which is featured by the synergy of Nine-Connotation; the hierarchy of the complex giant system; and the integration of construction, operation, and maintenance. The framework comprehensively covers all situations with a clear hierarchy that can achieve real-time evaluation.

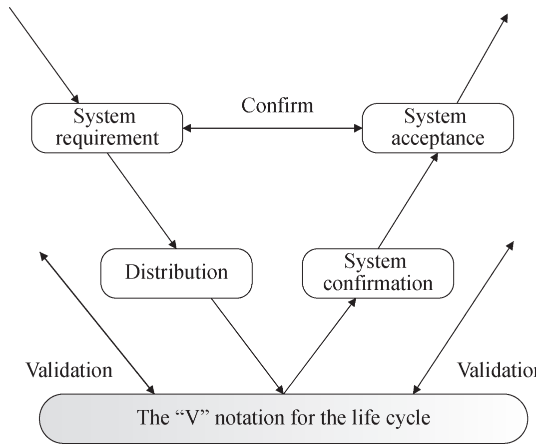

Fig. 7 RAMS model.

The cores of the reliability guarantee framework consist of a resilience management system, an integrated technology system, and dynamic reliability evaluation. The resilience management system includes organization, regulation, excitation, and integrated rescue. The integrated technology system includes rational standard, structural reliability, intelligent perception, maintenance intelligence, active recovery, and rescue effectiveness. Dynamic reliability evaluation covers different levels of reliability evaluation, such as unit level, subsystem level, and giant system level. The three levels are interrelated, in which the innovations in technology and management can

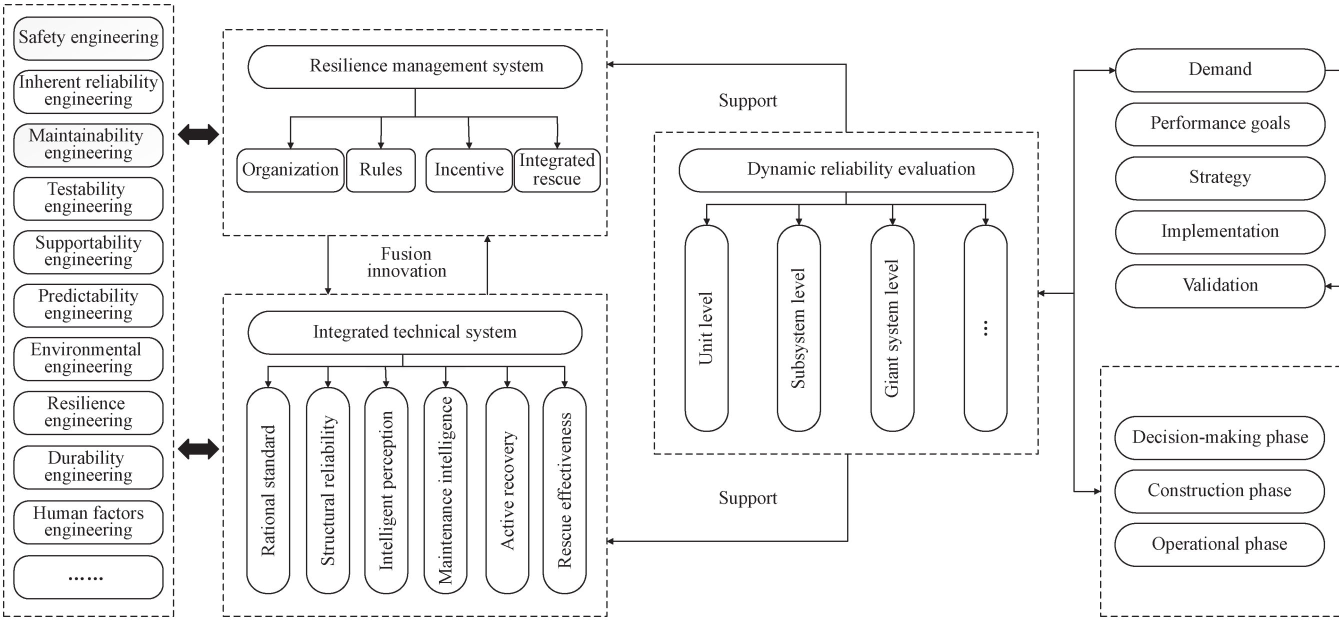

Fig. 8 Reliability guarantee framework for the Sichuan–Tibet Railway.

coordinately promote the development of each other. Furthermore, they can be optimized and improved by the dynamic reliability evaluation in return.

The reliability guarantee framework for the Sichuan–Tibet Railway reflects the time dimension of full life cycle management, the target dimension based on efficiency, the comprehensive guarantee dimension, and the knowledge dimension of multi-system engineering, which involves five principles, eleven particular projects, and *N* innovative applications.

Five principles: The reliability guarantee framework is deconstructed from the perspective of the life cycle reliability management, namely, identifying tasks requirements, making proper planning strategy, studying design countermeasures, proposing evaluation methodology, and providing safeguard measures, which not only covers the complete reliability management but also provides unified principles for the specific implementation.

Eleven particular projects: These projects are the critical areas to be solved, including environmental characteristics and risk analysis, technology support, standard system, structural reliability, long life span, state awareness of engineering structures and environment, intelligent inspection, operation resilience, maintenance management, emergency rescue, and reliability assurance.

N innovative applications: These applications correspond to the innovative applications of technology, management, and evaluation under the eleven particular projects. For example, the innovative technology of materials in the project of long life span, along with its management system, can be applied in the life cycle management of the Sichuan–Tibet Railway.

5 Implementation pathway of reliability guarantee

The implementation pathway of reliability guarantee focuses on the technology, management, and evaluation systems. During the construction period, the three systems can be specified as support from innovative technology, integration of construction and management, and evaluation of process reliability.

(1) Support from innovative technology

Driven by the complex giant system demands, the management of panoramic innovation is needed, including omnibearing innovation, overall-process innovation, and overall-entity innovation (Chen et al., 2020b; Zeng et al., 2019). The Sichuan–Tibet Railway Technology Innovation Center can be founded. The goals and operating strategies are to build a world-class technology innovation ecosystem by integrating scientific, technological, and talent resources from home and abroad and cultivate industrial base with high-quality research output and trans-regional synergic innovation network. It consists of technologic innovation, industrial chain innovation, industrial cluster innovation, application innovation, and management innovation, with the idea of "Research First, Experiment First". It provides multi-level and multi-granularity support for identified key scientific problems and uncertain technical difficulties during the whole life cycle of megaprojects.

(2) Integration of construction and management

Integrated management is established from three aspects, namely, project, knowledge, and time. More specifically, it is the integration of participation and the main project, the subsystem components, and the management process. It is an essential information flow activity needed to be done by many advanced technologies (Naticchia et al., 2020; Zhong et al., 2020). The integration of construction and management can be realized by the digital Sichuan–Tibet management platform based on building information modeling and geographic information system. The simulation, monitoring, diagnosis, prediction, and control of the entire process management can be achieved through data identification, accurate status perception, real-time data analysis, decision-making models, and intelligent and accurate execution.

(3) Evaluation of process reliability

With identified tasks, structure, and environment states, process reliability comprising virtual and entity can be evaluated by knowledge-based engineering. Given the comprehensive and accurate data, indexes for probabilistic or quantitative evaluation are not easy to acquire. Thus, the project is divided into unit, subsystem, and system levels. Reliability can be assessed by quantitative or qualitative analysis, such that the performance uncertainty of tasks or the system can be evaluated in advance. Consequently, the corresponding countermeasures can be proposed. Ya'an–Xinduqiao and Bomi–Linzhi sections in the Sichuan–Tibet Railway should be selected to be the demonstration projects and should be constructed in advance. The pilot sections can assist in the optimization and adjustment of technology and management.

6 Conclusions

(1) This study reviewed research and applications of reliability in the field of military equipment, rail locomotive, and railway engineering. This study characterized the Sichuan–Tibet Railway as a complex giant system and investigated its features from different levels. On the basis of the top–down design concept for the first time, the goal of the reliability guarantee for the Sichuan–Tibet Railway is to optimize the operational efficiency, which is defined as the available and credible ability to complete target tasks.

(2) Nine-Connotation of reliability guarantee was proposed in this study, namely, safety, inherent reliability, testability, maintainability, supportability, environmental adaptability, predictability, resilience, and durability, to optimize the operational efficiency. Reliability transmission mechanism was analyzed, and reliability guarantee model was established, which redefines the design concept and goal-oriented and implementation methods of the railway complex giant system.

(3) A reliability guarantee framework was constructed for the life cycle management. It composed of the resilience management system, the integrated technology system, and the dynamic reliability assessment system. In addition, the implementation pathway in the construction was presented, including innovative technology, integration of construction and management, and evaluation of process reliability, which can provide the closed-loop management process among technological innovation, management policies, and optimization.

References

Chen F, Yuan Z M, Yan L, Xu W, Miao Y F, Gao B W (2020a). Reliability and safety evaluation of autonomous computer system of intelligent CTC in high speed railway. Acta Automatica Sinica, 46(3): 463–470 (in Chinese)

Chen H Q, Zeng S X, Su Q K (2020b). Towards management of panoramic innovation in megaprojects: The case of Hong Kong–Zhuhai–Macao Bridge Project. Management World, 36(12): 212–227 (in Chinese)

Chen S K, Mao B H, He T J, Liu J F, Liu H D (2006). Reliability evaluation of railway traction power supply system based on accident tree analysis. Journal of the China Railway Society, 28(6): 123–129 (in Chinese)

Cheng H, Han Y (2012). Systematic thinking of engineering management and engineering life cycle management. Journal of Southwest University (Philosophy and Social Science Edition), 14(2): 36–40 (in Chinese)

Cheng H B, Cao Y F, Wang J X, Zhang W, Zeng H (2019). A preventive opportunistic maintenance strategy for the catenary system of high-speed railways based on reliability. Journal of Rail and Rapid Transit, 234(10): 1149–1155

Ding S Z (2014). Engineering Project Management. 2nd ed. Beijing: China Architecture Publishing & Media Co., Ltd. (in Chinese)

Feng X, He S W, Li Y B (2019). Temporal characteristics and reliability analysis of railway transportation networks. Transportmetrica A: Transport Science, 15(2): 1825–1847

Gu S, Li K P (2019). Reliability analysis of high-speed railway network. Journal of Risk and Reliability, 233(6): 1060–1073

Hidirov S, Guler H (2019). Reliability, availability and maintainability analyses for railway infrastructure management. Structure and Infrastructure Engineering, 15(9): 1221–1233

Huang W H (2013). Reliability of large-scale natural gas pipeline network. Acta Petrolei Sinica, 34(2): 401–404 (in Chinese)

Jia C G, Song R, He S W, Chen S B (2015). Study on evaluation index system of railway industry safety production. Railway Transport and Economy, 37(3): 69–73 (in Chinese)

Kang R (2012). Fundamentals of Reliability & Maintenability & Supportability Engineering. Beijing: National Defense Industry Press (in Chinese)

Kang R, Wang Z L (2005). Theoretical and technical framework of reliability system engineering. Acta Aeronautica et Astronautica Sinica, 26(5): 633–636 (in Chinese)

Lu C F (2015). Innovation and practice for engineering quality management of high speed railway in China. China Railway Science, 36(1): 1–10 (in Chinese)

Lu C F, Cai C X (2019). Challenges and countermeasures for construction safety during the Sichuan–Tibet Railway Project. Engineering, 5(5): 833–838

Mahboob Q, Zio E (2018). Handbook of RAMS in Railway Systems—Theory and Practice. CRC Press

Meng X L, Wang Y H, Jia L M, Li L (2020). Reliability optimization of a railway network. Sustainability, 12(23): 9805

Naticchia B, Corneli A, Carbonari A (2020). Framework based on building information modeling, mixed reality, and a cloud platform to support information flow in facility management. Frontiers of Engineering Management, 7(1): 131–141

Nowak A S, Collins K R (2005). Reliability of Structures. Chongqing: Chongqing University Press

Qian X S (2005). A new field of science—Open Complex Giant System and its methodology. Urban Development Studies, (5): 1–8 (in Chinese)

Qin Y H, Lu N J (2011). Evolution of reliability in engineering systems. Journal of Northeastern University (Social Science Edition), 13(4): 295–299 (in Chinese)

Sun X J (2012). Review of military reliability assurance standards. Electronic Product Reliability and Environmental Testing, 30(1): 61–65 (in Chinese)

Yang Y (2011). Research on RAMS Evaluation for Power Supply System of High-speed Railways. Dissertation for the Doctoral Degree. Beijing: Beijing Jiaotong University (in Chinese)

Zeng S X, Chen H Q, Jin Z Z, Su Q K (2019). The evolution of mega project innovation ecosystem and enhancement of innovation capability. Management World, 35(4): 28–38 (in Chinese)

Zhang W Q (2017). Interpretation and enlightenment of generalized RAMS. Chinese Engineering Consultants, (10): 32–35 (in Chinese)

Zhong B T, Wu H T, Ding L Y, Luo H B, Luo Y, Pan X (2020). Hyperledger fabric-based consortium blockchain for construction quality information management. Frontiers of Engineering Management, 7(4): 512–527

Zhu M M (2021). A new framework of complex system reliability with imperfect maintenance policy. Annals of Operations Research, in press, doi: 10.1007/s10479-020-03852-w