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Innovative practice and organizational management of the "Dual-Configuration" scheme for high-speed comprehensive inspection and test trains

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Abstract

Purpose – This paper presents an investigation of the innovative "Dual Configuration" management model implemented in China's high-speed rail comprehensive inspection and test train initiative. Against the backdrop of continuous iteration in global railway technology, an evaluation is conducted of the advancements in organizational structure, resource allocation, and process standardization facilitated by this framework.

Design/methodology/approach – A systematic analysis is employed of multi-tiered collaborative mechanisms anchored in a matrix-based joint working group, complemented by a value-tree analytical method to quantify cost-benefit optimization across the full lifecycle of train assets. This integrated approach encompasses dynamic resource-scheduling protocols and comprehensive risk-control systems.

Findings – Results indicate the "Dual-Configuration" model achieves dual operational functionality within a unified platform, effectively compressing project duration and reducing lifecycle costs. Value tree analysis reveals multi-dimensional cost-saving mechanisms through platform sharing, consolidated maintenance systems, and parallel management processes. Field implementation validates that this model significantly enhances equipment utilization and mission responsiveness while supporting integrated Electric Multiple Unit (EMU) and inspection technologies.

Originality/value – Transferable management paradigms for high-speed rail system development and safety assurance are established in this research paper. The value-tree model provides a systematic framework for evaluating the economic benefits of dual-use platforms, offering quantitative decision-making support for complex infrastructure investments. Furthermore, concrete optimization strategies and cross-industry applications for the "Dual-Configuration" framework are proposed.

Keywords High-speed comprehensive inspection and test train, Dual-Configuration, Technological innovation, EMU technology

Paper type Research article

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1. Introduction

Electric Multiple Units (EMUs), as core operational assets of high-speed railways, drive technological innovation that directly influences transportation safety, system stability, and operational efficiency. This innovation further acts as a critical catalyst for national economic development and passenger experience enhancement (Lu & Zhang, 2018; Wang, Chen, Xu, Song, & Li, 2024a). China's EMU technological evolution demonstrates a distinct progression–from initial technology absorption to indigenous innovation–shifting its role from technology follower to peer competitor and finally to global leadership (Zhang, Chen, & Zhou, 2024). This trajectory highlights the strategic necessity of systematic research in advancing EMU technologies.

High-speed comprehensive inspection and test trains embody this innovation paradigm. These platforms concurrently enhance EMU performance capabilities and railway safety systems (Jia *et al.*, 2024). The development objective was explicit: utilize the 350 km/h Chinese Standard EMU platform to engineer a dual-purpose vehicle capable of (1) validating next-generation EMU subsystems and (2) conducting routine infrastructure inspections. This integrated methodology enables comprehensive performance evaluation under operational conditions, facilitating early identification of latent safety hazards.

China's 2008 introduction of its inaugural 250 km/h comprehensive inspection train signified a strategic shift from technology importer to exporter, reflecting maturing indigenous technical capabilities (Kang, Wang, & Li, 2012; Zhong, Li, Li, Cao, & Zhang, 2013).

Globally, high-speed comprehensive inspection trains emerged earlier in other technologically advanced nations, each adopting distinct development strategies. Japan's early "Doctor Yellow" series employed relatively fixed functional configurations, prioritizing high-precision routine inspections of existing lines. Conversely, certain European nations developed specialized testing platforms. For example, Italy's "Marco Polo" (ETR 500 Y1) focused predominantly on signaling systems and traction performance validation for high-speed railways. Nevertheless, these technologies have exhibited minimal evolution over the past two decades (Liu, Liang, & Wang, 2018; Xu, 2008). Recent scholarly attention has shifted predominantly toward China's high-speed comprehensive inspection train development, with limited contemporary research on international counterparts (Chen, 2017; Li, Wang, Kang, & Li, 2014; Wang, Wei, Yang, Fei, & Guo, 2024b; Ma & Gao, 2020).

Traditional comprehensive inspection vehicle development approaches increasingly exhibit limitations–including single-purpose platform designs, suboptimal resource allocation, and low asset utilization–when addressing rapidly evolving high-speed railway technologies and diversified inspection demands (Gao, 2021; Hao *et al.*, 2023; Rahimi *et al.*, 2021; Wang, Miao, Zhang, Huang, & Xu, 2025). To address these constraints, Chinese researchers proposed a dual-configuration management model during high-speed comprehensive inspection train development. This model integrates 2 rapidly interchangeable configurations–testing and inspection–on a unified train platform, delivering end-to-end technological lifecycle coverage from frontier technology validation to routine inspection applications, thereby overcoming conventional single-function platform limitations (Dai *et al.*, 2025; Ma & Gao, 2020; Yang *et al.*, 2024). This methodology constitutes both a sophisticated engineering innovation and a significant project management advancement, exhibiting interdisciplinary integration of management science and engineering technology. Building on this foundation, this paper rigorously evaluates the model's practical implementation and efficacy in coordinating technology validation with routine inspection tasks. It synthesizes empirical case studies and operational outcomes in high-speed railway EMU and inspection technology domains, providing actionable insights for sustaining China's high-speed rail technological advancement.

2. "Dual Configuration" scheme's organizational management and implementation framework

The "Dual-Configuration" scheme integrates 2 rapidly interchangeable functional configurations on a single high-speed comprehensive inspection train platform:

(1) A "test vehicle configuration" dedicated to implementing and validating emerging technologies in EMUs and inspection systems;

(2) An "inspection vehicle configuration" that activates standardized comprehensive inspection capabilities for routine track monitoring. This approach unifies technology validation with operational inspections through a "single-vehicle dual-use" paradigm, optimizing equipment utilization, accelerating R&D cycles, and minimizing lifecycle costs. To operationalize this complex innovation, structured investigations in organizational design, resource optimization, and process engineering established an implementation framework built upon matrix collaboration, dynamic resource scheduling, and standardized configuration-switching protocols. Examined from a management science perspective, the successful implementation of the "Dual-Configuration" scheme relies not only on technological integration but, more fundamentally, on a set of systematic management innovations. This system deeply integrates concepts from modern project management, organizational theory, and operations management. Its matrix-based joint organization addresses the need for cross-boundary collaborative governance in complex innovation projects. The dynamic resource allocation mechanism embodies the core tenets of the Resource-Based View and Dynamic Capabilities theory concerning the identification, integration, and reconfiguration of core resources to adapt to rapidly changing environments. The standardized configuration switching process represents a practical application of Business Process Reengineering and Standardization Management theory, aiming to achieve systemic improvements in efficiency, quality, and risk control through process optimization. The specific construction and practical logic of these three dimensions will be elaborated in the following sections.

2.1 Matrix-based joint project management organization

To enable efficient collaboration and seamless execution of the "Dual-Configuration" scheme amid multifaceted technology integration and phased transitions, a matrix-based joint project management organization was established at project initiation. This structure overcomes the limitations of conventional hierarchies by creating a collaborative ecosystem featuring centralized strategic decision-making, specialized technical competencies, and end-to-end functional accountability.

The matrix organization integrates 4 core units:

Joint working command center: Functions as the strategic decision-making hub and coordination authority, jointly directed by executive leadership and chief engineers from railway operator and manufacturer entities. It establishes unified command protocols and cross-organizational information systems to ensure goal alignment, synchronized resource allocation, and operational consistency between configurations.

Overall technical team: Serves as the system architect and technical authority. Comprising domain experts from partner organizations, this team formulates the integrated technical strategy for "Dual-Configuration" implementation, defines interface specifications and functional boundaries between configurations, and resolves system integration challenges during configuration transitions to guarantee technical viability.

Specialized technology teams: Agile, temporary teams embedded within the matrix structure, assembled according to specific technological requirements of the "Dual-Configuration" system. These units deploy domain-specific expertise to resolve targeted technical challenges, sustain specialized competency levels, and advance innovation frontiers.

Business work group: Ensures contractual integrity and resource optimization. This unit manages procurement, contractual compliance, and intellectual property stewardship across both configuration phases, enabling legal adherence, resource efficiency, and systematic technical documentation management.

The matrix-based joint project management organization is not just a simple collaboration among units but an organic entity characterized by task orientation and bidirectional reporting mechanisms. It successfully integrates vertical professional management with horizontal project management, providing robust organizational support for the entire lifecycle management of this innovative “Dual-Configuration” project. A schematic representation of the management practices is provided in Figure 1.

The specific architecture and collaborative logic of this matrix-based joint project management organization are illustrated in Figure 1. Its operation adheres to the principles of hierarchical collaboration and information closed-loop control with 3 layers:

Decision and Coordination Layer: Centered on the Joint Working Group Command Department, this layer is responsible for strategic decision-making aligned with the dual objectives of “testing” and “inspection”, cross-organizational resource coordination, and critical issue resolution. The Command Department issues task directives and objectives to the execution layer and receives progress feedback and risk reports from it, forming a closed-loop decision-making cycle.

Core Execution Layer: This layer comprises the Overall Technical Group and multiple Specialized Technical Groups. The Overall Technical Group acts as the technical coordination hub, translating the Command Department’s objectives into overarching technical plans and decomposing tasks into more specific ones for the Specialized Technical Groups. Simultaneously, it integrates the technical outputs from the specialized groups for system integration and verification, and escalates major technical issues to the Command Department. Under the coordination of the Overall Group, the various Specialized Technical Groups

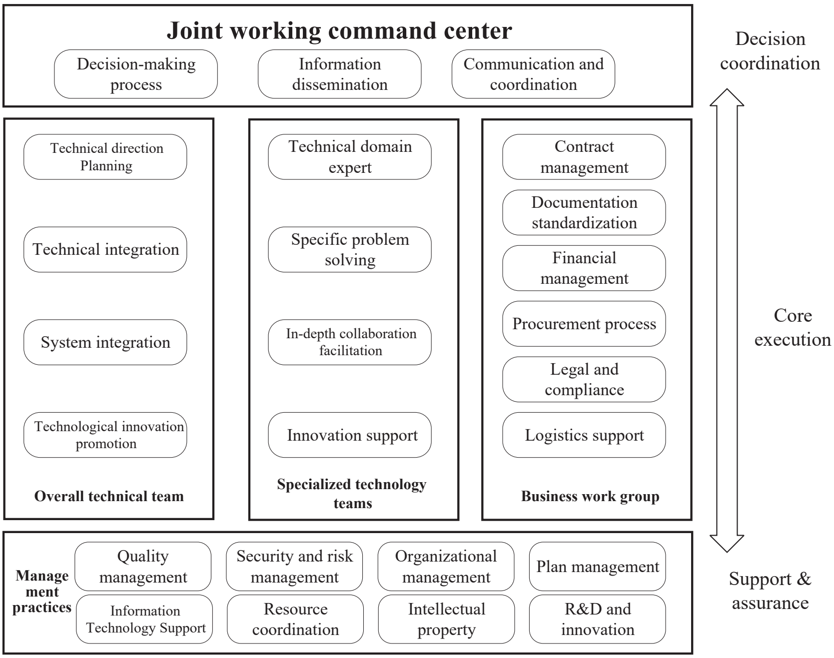

Figure 1. Management practice diagram. Source: Authors’ own work

conduct parallel work on research, testing, and data analysis within their specific technical domains, maintaining close technical interfaces and data exchange among themselves.

Support and Assurance Layer: The Business Working Group provides stable support for the entire project in contract management, procurement, resource allocation, and knowledge management. It receives resource deployment instructions from the Command Department and specific demands from the execution layer, delivers support services, and provides feedback on the support status to the Command Department.

Figure 1 clearly labels the key information flows, command flows, and feedback flows (indicated by bidirectional arrows) among these 3 layers and within the modules. This visual framework fully reveals the intrinsic operational logic of "Dual-Configuration" management within a dynamic collaborative environment.

2.2 Dynamic resource allocation mechanism based on stage goals

To support the efficient transition of the "Dual-Configuration" system across different phases, the project established a dynamic resource scheduling mechanism. In this project, core resources such as the technical expert team, specialized testing equipment, and scarce time windows on newly built lines constituted such strategic assets. In terms of management practice, resources were not allocated statically. Instead, they were identified through forward-looking planning, integrated via flexible scheduling, and their purposes were reconfigured according to phased objectives. This approach ensured the maximized utilization of strategic resources throughout the entire lifecycle.

To facilitate the efficient transition and execution of "test vehicle configuration" and "inspection vehicle configuration" across different task stages, the project team developed a dynamic resource allocation and scheduling mechanism based on stage-specific goals. The objective is to utilize forward-looking planning to guide resource preparation, enable flexible scheduling in response to task variations, and ensure precise deployment and seamless integration of key resources–such as personnel, equipment, and tracks–throughout the project's lifecycle.

2.2.1 Forward-looking planning. At the project's inception, the joint working group recognized integrated resource management as crucial for the successful implementation of the "Dual Configuration". To achieve this, they established a unified command and coordination mechanism centered around the overall team. This aimed to systematically identify the resource needs for testing and configuration switching at various stages, dynamically adjusting the allocation of critical resources like personnel, equipment, and tracks.

During the two-phase installation tests involving different manufacturers' technical equipment, the overall team effectively served as the "command center". They preemptively identified and reserved essential technical personnel and specialized debugging equipment for each phase. Through this forward-looking resource coordination and reservation approach, the project ensured that during the tight installation windows, critical resources could be dedicated and seamlessly deployed, providing a solid foundation for the efficient execution and smooth progression of test tasks.

2.2.2 Flexible scheduling. The overall technical team took on the role of the "resource scheduling center". When conducting comparative validations of different manufacturers' technical equipment, rather than rigidly following the original plan, the overall team dynamically issued "resource scheduling instructions" based on real-time progress and priorities. Personnel were allocated to form cross-unit test teams. Team members were fully engaged in data collection and fault diagnosis during testing phases, then returned to their regular duties during configuration switching and inspection phases. This approach ensured optimal utilization of human resources. Track resource scheduling involved coordinated planning with the joint commissioning and testing command center for newly built tracks still in the commissioning phase. The entire resource scheduling strategy adhered to a clear division: prioritizing scientific testing before moving to type testing. During the early stages of the project's test vehicle configuration, track resources were focused on ensuring on-site testing and validation of new technologies. Once the train switched to the inspection vehicle configuration, the primary task became completing type testing and system calibration to verify its performance as a qualified "comprehensive inspection vehicle". This phased resource allocation strategy, tailored to different configuration goals, ensured focused task objectives and concentrated resource investments, thereby optimizing the utilization of track resources.

By implementing a dynamic resource allocation mechanism based on stage goals, the project team transformed static resource reserves into dynamic assurance capabilities. This ensured that all key tasks during the complex iterative process received timely and sufficient resource support, laying a strong foundation for achieving the overall project objectives.

2.3 Standardized configuration switching and risk management procedures

The essence of the "Dual-Configuration" transition is a highly complex systems engineering task involving multiple, intersecting disciplines. To ensure its efficiency, reliability, and safety, the project team did not merely patch the existing maintenance processes but undertook a fundamental process reengineering. This reengineering was physically based on modular design, guided by a core focus on risk control, and ultimately produced a refined, standardized six-phase switching procedure.

Firstly, the core concept of process reengineering is manifested in the deconstruction and redesign of the traditional sequential and ambiguous modification steps. The project team dismantled professional barriers, decomposing the conversion task into logically clear, value-adding activities such as "safety confirmation, module disassembly/assembly, system debugging, and functional verification". By standardizing the definitions of mechanical, electrical, and data interfaces, interface friction was fundamentally eliminated, enabling parallel operations and significantly compressing non-value-adding time.

Secondly, standardized management is key to ensuring the stable and repeatable execution of the reengineered process. Each phase is equipped with clear Standard Operating Procedures (SOPs), quality acceptance criteria, and cross-disciplinary collaboration nodes, allowing technicians from diverse backgrounds to "work from the same blueprint and to the same standards". Simultaneously, embedded risk checklists and control thresholds transform experience-based risk management into a quantifiable, auditable standardized risk control protocol, exemplified by mechanisms like dual-operator verification and parameter deviation alarms.

This system, by making tacit knowledge explicit, proceduralizing complex operations, and structuring risk control, not only guarantees the success of individual transitions but also creates replicable and transferable organizational process assets. It profoundly embodies the management principle that "standardization is the foundation of efficiency and quality".

During the testing process, the need for rapid replacement of new components requires trains to be designed with modularity and standardization in mind. This design enables quick and accurate equipment and system replacements, meeting both scientific experiment requirements and practical needs for comprehensive inspection vehicles. The project team established an interdepartmental collaboration mechanism to ensure close cooperation among technicians from diverse professional backgrounds, jointly participating in configuration conversion activities. Predefined conversion plans included detailed information on required time, specific steps, and expected outcomes, ensuring swift responses to emergencies and minimizing downtime.

By standardizing mechanical installation, electrical connections, and data communication interfaces, various test and inspection devices were integrated into independent "functional modules". This forward-thinking design addressed common interface matching challenges in traditional modifications, laying a robust foundation for efficient and reliable configuration switching. On top of modular hardware support, the project team developed a refined, sixstage configuration switching procedure. This procedure covered the entire process from initial safety status confirmation, modular component removal and installation, preliminary system debugging and calibration, to final functional verification and low-speed trial confirmation.

Each stage corresponded to specific operational guidelines, quality acceptance criteria, and cross-disciplinary collaboration points, incorporating risk checklists and control thresholds. These measures ensured that technicians from different professional backgrounds could perform efficient parallel operations according to procedural guidance and monitor potential risks in real time. Examples include setting safety lock checkpoints during safety status confirmation, implementing dual-person confirmation mechanisms for high-risk operations during module removal and installation, establishing parameter deviation warning mechanisms during system debugging, and executing graded testing strategies during functional verification. This comprehensive procedure transformed complex system conversion tasks into a series of standardized, repeatable operation sequences, significantly enhancing the efficiency and reliability of switching operations. Furthermore, through systematic risk management mechanisms, it ensured the integrity and consistency of train functionality and performance across different configurations, ultimately achieving rapid, smooth, and safe transitions between experimental platforms and inspection equipment roles. This comprehensive procedural system transforms the complex task of system reconfiguration into a series of standardized, repeatable operational sequences. It not only significantly enhances the efficiency and reliability of the switching operations but also, through systematic risk control and calibration procedures, fundamentally ensures the functional and performance integrity and consistency of the train's core systems–particularly the detection system–across different configurations. This lays a solid technical foundation for the high-quality execution of subsequent inspection tasks. The configuration switching process is illustrated in Figure 2.

3. Value tree model analysis of project cost-benefit

3.1 Value tree model structure

Section 2 systematically elaborated on the management innovations of the "Dual-Configuration" scheme across 3 dimensions: organization, resources, and processes. Natural questions arise: Do these complex management inputs and changes yield tangible economic value? What are its life-cycle benefits? To scientifically address these questions and establish a causal link between management practices and economic outcomes, this section introduces the value tree model for analysis. This model serves not only as an evaluation tool but also as a logical framework connecting management actions with value outcomes. It aims to clearly reveal how the matrix organization, dynamic resource mechanism, and standardized processes constructed in Section 2 ultimately drive the maximization of total project value

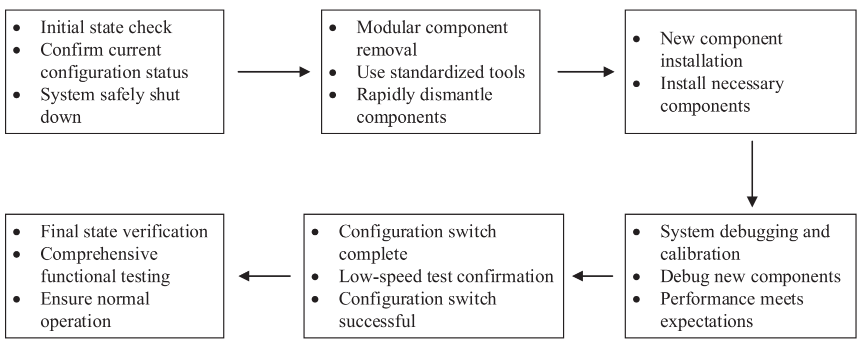

Figure 2. Configuration switching flowchart. Source: Authors' own work

through pathways such as cost savings and revenue enhancement. The following sections will first present the model structure, then elucidate its application through mathematical formulation and illustrative examples, and finally provide a systematic analysis of the value-creation logic of the “Dual-Configuration” scheme.

The full life-cycle cost-benefit optimization achieved through the “Dual Configuration” scheme can be systematically analyzed using a value tree model. As illustrated in Figure 3, this hierarchical model adopts “enhancing project value across its entire lifecycle” as its fundamental objective. Through successive decomposition of value components, the model explicitly demonstrates the value creation mechanism characterized by “single investment, dual returns”.

First Level: Core value objective.

At the root of the value tree lies the project’s ultimate value objective: “maximization of full life-cycle cost-effectiveness”.

Second Level: Key value drivers.

To operationalize this objective, two principal value drivers emerge as the central pillars of the model:

(1) Effective control of total input costs

(2) Significant enhancement of comprehensive output benefits

Third Level: Specific management initiatives and benefits.

Beneath these two primary value drivers, the model further decomposes into specific management initiatives and their corresponding benefit manifestations, establishing clear causal relationships between implementation actions and value outcomes.

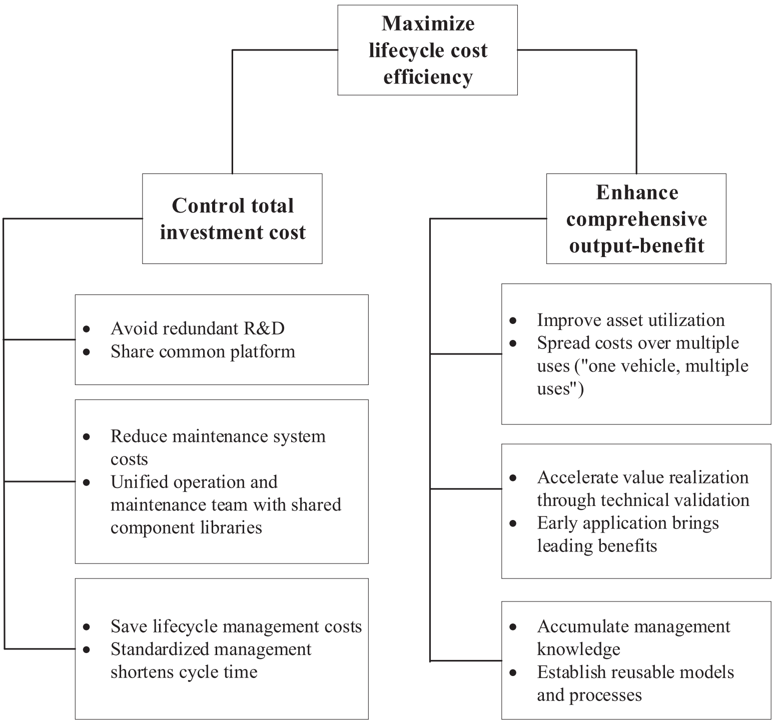

Figure 3. Value tree model analysis diagram. Source: Authors’ own work

3.2 Mathematical representation of the value tree model

To facilitate a quantitative understanding of the value tree model, the relationship between "total input cost control" and "comprehensive output benefit enhancement" can be formalized through the following mathematical equations:

The fundamental equation for full life-cycle value (V) is defined as Equation (1):

$$V = R - C \tag{1}$$

where (R) represents the comprehensive output benefits, and (C) denotes the total input costs.

Further decomposition reveals that the total input cost (C) comprises 3 principal components:

C_1: One-time capital investment, including initial project investment and equipment procurement costs.

C_2: Operational and maintenance costs, encompassing equipment repair expenses, labor costs, and energy consumption.

C_3: Ancillary costs, such as management overhead and administrative expenditures.

Thus Equation (2) can be derived:

$$C = C_1 + C_2 + C_3 \tag{2}$$

Similarly, comprehensive output benefits (R) can be categorized into 3 dimensions:

R_1: Direct economic benefits, including subsequent operational revenues and service fees.

R_2: Indirect economic benefits, such as cost reductions resulting from economies of scale and market share expansion.

R_3: Intangible benefits, including technological knowledge accumulation, organizational capability enhancement, and innovation capacity development.

Accordingly, Equation (3) can be expressed as:

$$R = R_1 + R_2 + R_3 \tag{3}$$

Rigorous analysis and strategic management of these variables enable the formulation of scientifically grounded decision-making frameworks. During the project planning phase, comparative cost-benefit analyses of alternative implementation strategies can be conducted to identify the optimal configuration that maximizes the life-cycle value (V). This analytical approach provides a systematic foundation for resource allocation decisions and strategic planning in complex infrastructure projects with dual functionality requirements.

3.3 Demonstration via illustrative examples

To make the analytical process of the value tree model more intuitive and actionable, and to demonstrate how it quantitatively assesses the benefits of the "Dual-Configuration" scheme, this section introduces a set of hypothetical parameters based on industry experience to perform illustrative calculations using the equations presented in the context.

There are 4 assumed conditions:

(1) The proportion of the basic platform R&D cost to the total R&D and design cost of a single project is $\alpha = 0.3$ (i.e., 30%).

(2) After implementing the "Dual-Configuration" parallel management, the total project duration is shortened by $\Delta T = 0.5$ years compared to the traditional serial mode.

(3) The total project investment is I = 10 billion CNY, with an annual capital interest rate r = 5%.

(4) The actual utilization time of the asset under the "Dual-Configuration" mode, T (Dual-Configuration Use), is 40% higher than that under the traditional mode, T (Traditional Use) (e.g., 6 months per year in the traditional mode vs. 8.4 months per year in the Dual-Configuration mode).

Then, the benefit estimation can be derived based on the above assumptions:

(1) Cost savings from platform sharing

According to Equation (1), the R&D and design cost savings for a subsequent project are: ΔC (>R&D) = $\alpha \cdot$ C (R&D) = 0.3 $\cdot$ C (R&D). This indicates that by sharing the basic platform alone, a follow-up similar project can save approximately 30% of its R&D and design investment.

(2) Benefits from cycle compression via parallel management

According to Equation (5) and (6), the cost savings resulting from cycle compression can be estimated as:

Project Management Cost Savings: Assuming the unit-time project management cost C (Management) = 2 million CNY/year, then C (Saving 4) = 2 million CNY/year $\cdot$ 0.5 years = 1 million CNY.

Capital Occupation Cost Savings: C (Saving 5) = 10 billion CNY $\cdot$ 5% $\cdot$ 0.5 years = 25 million CNY.

Thus, the direct and indirect cost savings from shortening the cycle by 0.5 years amount to 26 million CNY from these two items alone.

(3) Improvement in asset utilization

According to Equation (7) and (8), assuming the asset utilization rate in the traditional mode U (Traditional) = 6 months/12 months = 50%, then the utilization rate under the "Dual-Configuration" mode U (Dual-Configuration) = 8.4 months/12 months = 70%. The relative improvement in asset utilization is: (70% − 50%)/50% = 40%. This visually demonstrates the effect of the "one-vehicle-dual-use" model in activating the idle time of the expensive inspection platform.

In summary, the above illustrative calculations show that the value tree model can deconstruct and quantify the abstract "cost-benefit" advantages of the "Dual-Configuration" scheme into multiple specific, assessable indicators. Although actual project parameters vary, this model provides a universal analytical framework. Decision-makers can input specific cost, time, and resource data to systematically evaluate the incremental life-cycle value (V) of the "Dual-Configuration" management model compared to traditional solutions, thereby providing quantitative support for management decisions.

3.4 Analysis of the "Dual Configuration" scheme based on the value tree model

3.4.1 Control of total input costs: saving mechanisms of multi-dimensional cost.

(1) Shared basic platform

By sharing fundamental platforms such as the train body and bogies, significant savings can be achieved in the R&D design and industrial manufacturing costs associated with a second vehicle. Leveraging a modular design philosophy, sharing core foundational platforms like the train body and bogies avoids the need for repeated R&D and manufacturing investments across multiple projects. From a cost allocation perspective, when several projects are developed based on a unified foundational platform, the basic module's R&D costs do not need to be recalculated for each project; instead, only marginal improvement costs need to be covered.

Let $C_{R\&D}$ represent the total R&D design cost for a single project, where the proportion of foundational platform R&D costs is α ($\alpha \in (0,1)$). Therefore, the direct savings in R&D design costs for the second project through shared foundational platforms can be expressed as Equation (4):

$$Savings = C_{R\&D} \times \alpha \tag{4}$$

(2) Consolidation of operations and maintenance systems

A unified operations and maintenance team and a shared spare parts library avoid the need for human resources, equipment, and facility investments required to establish 2 independent maintenance systems.

On one hand, a unified operations and maintenance team centralizes professional technical personnel, improving workforce utilization efficiency and avoiding issues such as personnel redundancy and dispersed professional skills that arise from maintaining separate maintenance teams. Assuming the personnel cost for each independent maintenance team is $C_{\text{personnel}}$, and the equipment and facility cost is $C_{\text{equipment\&facilities}}$, the saved human resource cost C_{savings2} after adopting a unified maintenance team can be expressed as Equation (5):

$$C_{\text{savings2}} = C_{\text{personnel}\,(\text{the second independent team})} \tag{5}$$

On the other hand, a shared spare parts library can reduce procurement and inventory costs through centralized purchasing and optimized inventory management. Assuming the inventory costs of establishing 2 independent spare parts libraries are $C_{\text{inventory1}}$ and $C_{\text{inventory2}}$, and the inventory cost after adopting a shared spare parts library is $C_{\text{shared inventory}}$, the saved inventory cost C_{savings3} can be expressed as Equation (6):

$$C_{\text{saving3}} = C_{\text{inventory1}} + C_{\text{inventory2}} - C_{\text{sharedinventory}} \tag{6}$$

(3) Parallel management

Optimizing traditional sequential project task processes into a partially parallel mode reduces indirect costs such as project management and capital occupancy by shortening the overall project cycle. The specific derivation is as follows:

Assuming the total project cycle under traditional project management mode is $T_{\text{traditional}}$, and the total project cycle under parallel task management mode is T_{parallel}, the shortened project cycle ΔT is shown in Equation (7):

$$\triangle T = T_{\text{traditional}} - T_{\text{parallel}} \tag{7}$$

In terms of project management cost savings, assuming the project management cost per unit time is $C_{\text{management}}$, the saved project management cost C_{savings4} is expressed in Equation (8):

$$C_{\text{saving4}} = C_{\text{management}} \times \triangle T \tag{8}$$

In terms of capital carrying cost savings, assuming the total project investment is I and the annual interest rate is r (calculated based on 365 days), the saved capital carrying cost C_{savings5} is embodied in Equation (9):

$$C_{\text{saving5}} = \frac{I \times r \times \triangle T}{365} \ (\text{Assuming 365 days in a year}) \tag{9}$$

3.4.2 Enhancing comprehensive output benefits: asset efficiency and revenue optimization. Under the dual-task configuration model, the same asset undertakes 2 core tasks, resulting in significantly higher utilization intensity and value-creating capability compared to single-function assets. This improves asset utilization and spreads the fixed costs per task. The specific derivation is as follows:

(1) Improvement in asset utilization

Asset utilization is a core indicator measuring the efficiency of asset usage, defined as the ratio of the actual effective usage time of the asset to the total available time. Let the total available time of the asset be T_{total}, the actual usage time under the traditional model be $T_{\text{traditional usage}}$, and the actual usage time under the "dual-configuration" model be $T_{\text{Dual-Configuration usage}}$. The asset utilization rates under the 2 models are shown respectively in Equation (10) and Equation (11):

$$U_{\text{traditional}} = \frac{T_{\text{traditional}}}{T_{\text{total}}} \tag{10}$$

$$U_{\text{dual-configuration}} = \frac{T_{\text{dual-configuration}}}{T_{\text{total}}} \tag{11}$$

Since $T_{\text{dual-configuration usage}} > T_{\text{traditional usage}}$, it follows that $U_{\text{dual-configuration}} > U_{\text{traditional}}$, indicating that the dual-task configuration achieves a significant improvement in asset utilization.

(2) Accelerated technology verification

Accelerated technology verification represents an extended value of parallel task management. Its core mechanism involves partially parallelizing the technology verification phase with the core development process, thereby compressing the implementation cycle for new technologies and processes and amplifying the benefits of "early verification, early application".

In addition to these efficiency gains, this approach delivers 2 further strategic benefits:

Technology leadership benefits: the early deployment of new products and processes enables the capture of first-mover advantages in operational scenarios, forming differentiated technological competitiveness, with benefits manifested as the establishment of early barriers in market/operational domains.

Operational safety benefits: earlier real-world scenario verification allows for the premature exposure of potential technical risks, avoiding safety hazards associated with large-scale application, with its indirect value reflected in the preemptive mitigation of risk management costs.

(3) Management knowledge accumulation

The "Dual-Configuration" management model, standardized processes, and collaboration mechanisms developed in this project inherently constitute a valuable intangible asset that can be reused in future projects, generating long-term value. This set of models and processes can be directly replicated in similar future projects, avoiding the management trial-and-error costs associated with redundant exploration. The accumulated management knowledge will be transformed into the organization's core capabilities, optimizing resource allocation and task coordination efficiency in subsequent projects, with its long-term value demonstrated through the continuous reduction of the organization's marginal management costs. The value of such intangible assets is not confined to a single project but is amplified through a cycle of "reuse-iteration-reuse", achieving sustained management benefits.

In summary, the "Dual-Configuration" solution is not merely a functional overlay but a systematic practice of value engineering. This approach optimizes resource allocation at the decision-making source and achieves cost savings and efficiency improvements across the entire chain–including R&D, manufacturing, operations, and maintenance–through top-level design, ultimately maximizing the net value over the project's entire lifecycle. The "dual-purpose vehicle" model, constructed based on the "Dual-Configuration" management concept, demonstrates significant comprehensive benefits throughout the project lifecycle. By integrating both testing and inspection functions on a single train platform, this model effectively avoids the redundant resource investments associated with developing dedicated testing and inspection vehicles separately under traditional approaches. It not only directly saves the high costs of vehicle redevelopment, redundant system development, and independent later-phase operations and maintenance but also substantially enhances the platform's functional density and lifecycle value.

4. Conclusions and prospects

4.1 Conclusions

This paper conducts a systematic investigation and practical summary of the innovative "Dual-Configuration" management model in the development of high-speed rail comprehensive inspection and test trains. The main conclusions are as follows:

(1) An efficient and collaborative matrix-style joint project management organization was established, overcoming the barriers to cross-organizational and cross-disciplinary coordination. As described in Section 2.1, this organization centers on a command department as the decision-making hub, with overall and specialized technical groups serving as the technical engine and a business group providing support. It forms a matrix structure that deeply integrates vertical professional management with horizontal task management. This governance model ensures the alignment and synchronization of the dual objectives–"testing" and "inspection"–throughout the complex project lifecycle, providing a solid organizational foundation for innovative practices.

(2) A dynamic resource allocation and scheduling mechanism based on phased objectives was developed, enabling the efficient utilization of core resources. The analysis in Section 2.2 shows that through forward-looking planning and flexible scheduling, the project achieved precise deployment and seamless integration of key resources–such as personnel, equipment, and line access–across different task phases. This mechanism reflects the management capability to dynamically integrate and reconfigure strategic resources in a rapidly changing project environment and is key to ensuring the smooth operation of the "one-train-dual-use" process.

(3) A standardized configuration-switching and risk-control process was established, ensuring the efficiency, safety, and reliability of functional transitions. As elaborated in Section 2.3, based on modular design and through a refined six-phase switching procedure with embedded risk-control checkpoints, the complex system transition task was transformed into a standardized, repeatable operational sequence. Feedback from field applications indicates that this rigorous process effectively ensures the reliable restoration and maintenance of the detection system's baseline performance after the train is converted from the test configuration to the inspection configuration, thereby supporting the high-quality execution of inspection tasks.

(4) The significant advantages of the "Dual-Configuration" model in terms of lifecycle cost-effectiveness were demonstrated through the value-tree model. The analysis in Section 3 reveals that this model effectively controls total input costs through pathways such as shared basic platforms, consolidated operation and maintenance systems, and parallelized management. Simultaneously, it significantly enhances comprehensive output benefits by improving asset utilization, accelerating

technology validation, and accumulating management knowledge. This validates the comprehensive value of the aforementioned management innovations from an economic perspective, indicating that the "Dual-Configuration" is a systems engineering approach that balances technical feasibility with economic rationality.

In summary, through systematic innovations in organization, resources, processes, and evaluation systems, the "Dual-Configuration" management model successfully achieves the functional integration and efficient operation of technology-validation platforms and routine inspection equipment. It provides a referable paradigm for the development and asset management of major high-speed rail technical equipment in China.

4.2 Prospects

Based on the practices and conclusions of this study, future work can be further deepened and expanded in the following aspects:

(1) Promoting the institutionalization and standardization of the management model

It is recommended to incorporate the whole-lifecycle optimization philosophy, such as the "Dual-Configuration" approach, into industry guidance policies. Support should be provided for relevant stakeholders to lead the development of technical and management standards for "multi-functional, reconfigurable" inspection and test platforms, thereby facilitating the standardized promotion of innovative practices.

(2) Strengthening interdisciplinary research and talent development

The success of the "Dual-Configuration" model reflects the deep integration of management science and engineering technology. In the future, more cross-disciplinary research projects should be encouraged, and compound talents who are proficient in both cutting-edge technology and modern project management should be cultivated to address the challenges of innovating more complex equipment systems.

(3) Expanding the application scenarios and ecosystem of the model

The inherent logic of this management model–such as dynamic resource scheduling and flexible functional configuration–could be explored for application in fields like urban rail transit and large-scale scientific research infrastructure. At the same time, consideration should be given to building a more open innovation ecosystem by opening such platforms to the industrial chain, thereby accelerating technological iteration and transformation.

(4) Exploring digital empowerment and continuous optimization

Follow-up research could focus on leveraging technologies such as digital twins and big-data simulation to dynamically simulate and continuously optimize the configuration-switching processes and resource-scheduling strategies. This would further enhance the economic efficiency, adaptability, and decision-making rigor of this management model.

References

Chen, C. (2017). Study on development of CRH380AM-0204 high speed comprehensive inspection train. *China Railway*, *10*, 69–76.

Dai, P., Li, H. L., Wang, F. D., Tian, X. Y., Wang, H., & Xu, X. D. (2025). Key technologies of China high-speed comprehensive inspection train: CIT450. *Railway Engineering Science*, *33*(3), 414–440. doi: 10.1007/s40534-024-00362-4.

Gao, S. (2021). Automatic detection and monitoring system of pantograph-catenary in China's high-speed railways. *IEEE Transactions on Instrumentation and Measurement*, *70*, 3502012. doi: 10.1109/tim.2020.3022487.

Hao, X., Yang, J., Yang, F., Sun, X., Hou, Y., & Wang, J. (2023). Track geometry estimation from vehicle-body acceleration for high-speed railway using deep learning technique. *International Journal of Vehicle Mechanics and Mobility*, *61*(1), 239–259. doi: 10.1080/00423114.2022.2037669.

Jia, B., Shen, J., Chen, L., Wang, Y., Zheng, W., & Guo, W. (2024). Operation safety control measures and technical innovation for test EMU during integrated commissioning & test. *China Railway*, 5, 16–23.

Kang, X., Wang, W. D., & Li, H. L. (2012). Research on key technologies of high-speed comprehensive inspection train. *China Railway*, 10, 3–7.

Li, H., Wang, W., Kang, H., & Li, H. (2014). Overall architecture design of CRH380B-002 high-speed comprehensive inspection train. *Railway Engineering*, 2, 109–112.

Liu, K., Liang, Z., & Wang, J. (2018). The high speed comprehensive inspection train in alpine region. *Rolling Stock*, *56*(5), 29–31.

Lu, C., & Zhang, J. (2018). High-speed railway technology innovation and engineering construction management. *China Occupational Safety and Health*, *13*(4), 8–10.

Ma, K., & Gao, D. K. (2020). Research and development assumption for high-speed comprehensive detection test train. *Urban Mass Transit*, *23*(2), 79–83.

Rahimi, M., Liu, H., Rahman, M., Cárcel, C., Durazo-Cardenas, I., Starr, A., . . ., & Anderson, R. (2021). Localisation and navigation framework for autonomous railway robotic inspection and repair system. In *TESConf 2021: Design*.

Wang, L., Chen, C., Xu, H., Song, Q., & Li, C. (2024a). Plane layout and passenger interface design of a new generation high-speed EMU. *China Railway*, 6, 90–98.

Wang, Y., Wei, S. B., Yang, F., Fei, J. Y., & Guo, J. F. (2024b). Development of track geometry inspection equipment for high-speed comprehensive inspection train in China. *Railway Sciences*, *3*(6), 673–683. doi: 10.1108/rs-08-2024-0030.

Wang, Y., Miao, B., Zhang, Y., Huang, Z., & Xu, S. (2025). Review on rail damage detection technologies for high-speed trains. *Applied Sciences*, *15*(14), 7725. doi: 10.3390/app15147725.

Xu, G. (2008). Research and application of comprehensive train inspection technology scheme for passenger dedicated lines. *Railway Engineering*, 2, 95–98.

Yang, C., Liu, K., Li, H. L., Liang, Z., Wu, Q., & Liu, W. (2024). Development of the Fuxing high-speed comprehensive inspection train. *China Railway*, 11, 69–75.

Zhang, Y., Chen, K., & Zhou, Z. (2024). The mechanism of industry-university-research institute collaboration innovation for catching up in industrial core technologies in latecomer countries: A case study based on China's high-speed rail industry. *Journal of Management World*, *40*(11), 20–48.

Zhong, C. C., Li, H. K., Li, P., Cao, Y., & Zhang, Y. Z. (2013). Overview of high-speed comprehensive inspection train. *China Railway*, 6, 89–93.

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