Research on the Business Application Layer in the Technical Framework of Road Infrastructure Digital System

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Abstract. Driven by both the digital economy and new technologies, the construction of digital road infrastructure continues to advance, yet its technical and economic characteristics and development patterns still require deeper exploration. This paper centers on the business application layer of digital road infrastructure systems. It opens with an overview of the scale of China's transportation infrastructure and the backdrop of its digital transformation, highlighting the significance of the research.The business application layer has achieved fruitful results at various stages: in the survey and design phase, diverse methods such as forward design using physical models, BIM-based collaborative design, and virtual model design are implemented in parallel, enhancing the quality and efficiency of design; in construction management, the combination of prefabricated assembly with BIM and RFID, along with digital recording, ensures efficient construction; in operation and maintenance, reverse BIM applications involve multiple key steps, enhancing the precision of maintenance; and in travel services, the MaaS system integrates resources to optimize user travel experiences.However, current construction efforts are plagued by issues such as technological immaturity and a lack of top-level design. There are bottlenecks in technology across various links, and the top-level planning lacks a coordinated framework. Industry standards and processes are chaotic, and the integration of data and models is hindered. Therefore, strengthening technological integration, optimizing top-level coordination, and enhancing service quality are crucial. By doing so, we can promote orderly and efficient construction, contribute to the modernization of transportation, and support the innovative development of the economy and society.

Keywords: BIM; Digital; Road Infrastructure; Collection and Perception Layer.

1. Introduction

By 2020, China's comprehensive transportation network had reached a total mileage of 5,012,500 kilometers, with high-speed railways exceeding 35,000 kilometers and expressways spanning 149,600 kilometers[1].As technology evolves, infrastructure has undergone a transformation from low-grade roads to highways, and further to digitalized and intelligent highways, striving towards the goals of ultra-performance and green roads in the future. In May 2024, the Ministry of Finance and the Ministry of Transport jointly issued the "Notice on Supporting and Guiding the Digital Transformation and Upgrading of Highway and Waterway Transportation Infrastructure," outlining the implementation path for advancing the digital transformation, intelligent upgrading, and fusion innovation of highway and waterway transportation infrastructure over the next three years. This notice is of great significance for accelerating the construction of a powerful transportation nation and promoting high-quality development in the transportation sector. The digital transformation and upgrading of transportation infrastructure takes data resources as a key element, with the integrated application of information and communication technologies and the full-element digital transformation serving as important driving forces. By deeply applying new technologies such as big data, the Internet of Things (IoT), artificial intelligence, and Beidou Navigation Satellite System, it promotes the smart expansion, safety and efficiency enhancement, and industrial integration of transportation infrastructure, realizing process reengineering, system reshaping, and institutional restructuring within the transportation industry. Thus, the digitization of road infrastructure represents a crucial pathway for future development in the transportation sector.

This article delves into the technical framework of digital systems for road infrastructure, focusing on the business application layer, which constitutes one of the three parts of the technical framework. The business application layer, located in the middle to upper tier of the technical framework, primarily relies on data support provided by the lower layers to realize various business functions and services. It transforms data into valuable information and knowledge, supporting the digital management and intelligent applications of road infrastructure. A deeper understanding of the technical framework of digital systems for road infrastructure is gained through examining three modules: survey and design, construction management, and operation, maintenance and repair of road projects[2].

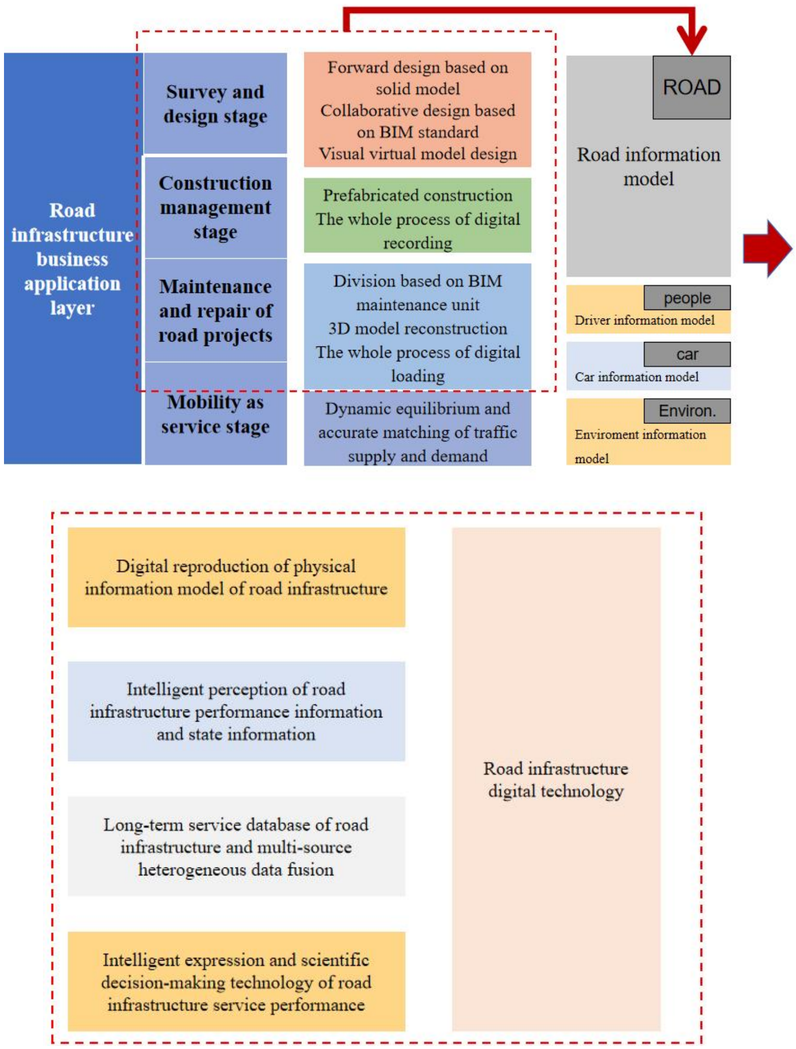

Fig. 1 Highway Infrastructure Business Application Technology System

2. Stage

2.1 Survey and design stage

2.1.1 Forward design based on solid model

The forward design process of physical models requires orderly and efficient coordination and management of BIM data flow and workflow. In this process, the BIM data flow represents the transmission pathway of design outputs, while the workflow defines the logical sequence of various work steps[3]. From the initial stage of forward design, related structures such as roads, bridges, culverts, and tunnels are integrated into the terrain as three-dimensional entities, and the final deliverable is a complete set of three-dimensional model systems. The focus at this stage is on the rapid construction capability of physical models [4], which aims to significantly enhance modeling efficiency and reduce cost expenditures at various stages, thereby allocating more resources to the survey and design aspects of road infrastructure.

2.1.2 Collaborative design based on BIM standard

The essence of collaborative design lies in efficiently assembling and utilizing design resources, optimizing the interaction processes among various design parameters, and creating an interconnected data logic system, thereby constructing a collaborative design environment based on a unified data foundation. The advent of BIM technology has spurred the concept of three-dimensional collaborative design. The outputs produced under this design mode are intuitive and straightforward, greatly simplifying the communication process between the constructor and the designer, and effectively avoiding communication barriers caused by differences in understanding of two-dimensional drawings[5].

2.1.3 Visual virtual model design

The application of Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) technologies can significantly enhance the performance capabilities of BIM and expand its boundaries of application. Integrating BIM models into a VR environment can incorporate subjective perceptual information beyond traditional BIM data, thereby enhancing the engagement and immersion of stakeholders across multiple domains[6].

2.2 Construction management stage

2.2.1 Prefabricated construction

Initially, the integration of BIM technology with RFID technology ensures precise data acquisition and effective data transmission. By embedding RFID tags in building components and utilizing their unique identification features, we can achieve comprehensive digital management throughout the entire process of component production, storage, transportation, and installation[7]. During the construction phase, this integration helps reduce inventory costs and minimize material waste. In the construction management aspect, real-time tracking of building components allows us to effectively prevent situations where required components are misplaced or incorrectly identified on the construction site, thereby significantly boosting construction productivity.

2.2.2 The whole process of digital recording

In the process of road infrastructure construction, the construction management phase plays a crucial role. This phase necessitates the holistic integration of various aspects, including construction processes, technology application, and personnel allocation. It is particularly essential to promptly and accurately feedback the diverse information generated continuously during the construction process, such as the actual conditions at the construction site and the execution effectiveness of construction techniques, into the digital model. By doing so, any improper actions in the implementation progress, such as unreasonable construction sequences or uneven resource allocation, can be swiftly identified and adjusted, thereby optimizing the overall design and ensuring the construction project progresses efficiently and with high quality.

2.3 Maintenance and repair of road projects

In the maintenance and management phase of road infrastructure, the application approach of BIM diverges from that in the design and construction phases. While BIM is typically implemented in a forward manner during design and construction, it is more often applied in reverse during maintenance and management. Except for a few infrastructures with comprehensive information models, digital modeling based on existing facilities is often necessary to swiftly establish as-is models in most cases.

To establish a BIM system suitable for the maintenance phase, the following five key steps are essential:

Firstly, segment the maintenance units based on BIM. It is necessary to create BIM units specifically for infrastructure maintenance, which can adapt to more complex modeling scenarios and carry multi-dimensional and dynamically changing data.

Secondly, reconstruct the 3D models. Reverse 3D digital modeling is achieved with the aid of scanning technology for physical infrastructure projects.

Thirdly, conduct digital loading for the entire process. On the basis of the completed BIM model for road infrastructure, engineering data from the entire lifecycle of infrastructure construction, management, and maintenance are added to ensure comprehensive data loading.

Lastly, develop system integration algorithms. Analysis and decision-making are based on as-is models to create a comprehensive business system covering maintenance monitoring, decision-making, design, construction, and post-evaluation. Interfaces for further development are reserved to provide robust technical support for maintenance and management tasks.

2.4 Mobility as service stage

Currently, road digitization applications at the business level continue to confront challenges such as information fragmentation, scattered infrastructure, and operational imbalance, necessitating the introduction of a demand-oriented Mobility as a Service (MaaS) system. This system aims to integrate diverse transportation services, ensuring a balance between user needs and transportation supply. Characterized by its flexibility, personalization, and high degree of randomness, MaaS essentially focuses on users, leveraging digital information as a crucial production resource to provide integrated supply-demand optimization solutions for various modes of transportation, thereby achieving dynamic equilibrium and precise matching between transportation supply and demand [8].

Additionally, road infrastructure serves as an adaptive platform for vehicular travel, fostering an interactive relationship with vehicles: vehicles provide holographic location and status information back to the roads, driving the evolution of the road transportation network towards digital integration. By integrating data sensing, integrated processing, and analytical algorithms within the realm of road infrastructure, we can offer users optimal transportation planning, enabling real-time information exchange between vehicles and roads.

The implementation of the MaaS system brings flexible, efficient, and user-friendly service experiences to travelers. It not only lays the foundation for building a real-time information data platform based on the four core elements of the digital transportation system (people, vehicles, roads, and the environment) but also marks a significant step in transitioning the transportation system from private to shared transportation and from discrete to integrated transportation[9].

3. Problems

In the grand layout of the "new infrastructure", road infrastructure, as an important field of practical application, has embarked on the path of integrated development with emerging technologies and has achieved certain breakthroughs in multiple cutting-edge areas such as the innovation of driverless technology, the precise application of Beidou satellite navigation, the construction of intelligent expressway systems, and the intelligent collaboration of urban brains. However, on the whole, the digitalization process of road infrastructure is still in an in-depth exploration stage. There are still many imperfections in the various technological systems it relies on. Whether in specific implementation strategies, innovative models of construction and operation, or in the diversified provision of services, further optimization and improvement are required. In the actual operation process, a series of complex problems have also emerged and need to be solved urgently.

During the digitalization process of new road infrastructure, there exists an incomplete and fragmented understanding of its underlying laws, coupled with a lack of adequate top-down guidance and comprehensive planning. Across the various stages of a road infrastructure's lifecycle, including survey and design, construction, maintenance, and travel services, an efficient and robust top-level architecture has yet to be established. Therefore, there is an urgent need to strengthen top-down guidance and achieve uniformity and standardization in top-level design, in order to ensure the orderly and efficient advancement of the digitalization of new road infrastructure.

Although there are methods such as forward design based on physical models, collaborative design using BIM standards, and virtual model design, these methods have not yet formed unified specifications and standard processes within the industry. Different projects or teams may adopt varying combinations of technologies and operational methods, leading to difficulties in data sharing, model integration, and other aspects. This makes it impossible to achieve efficient collaborative work and difficult to form a universally applicable top-level design framework across the entire industry.

In the implementation of measures such as the integration of prefabricated buildings with BIM and RFID technologies, as well as full-process digital recording, the degree of application and technical proficiency varies among construction units. Some enterprises may be constrained by factors such as costs and technical talent, making it impossible for them to fully leverage the advantages of these technologies. Additionally, there is a lack of unified industry guidance to standardize digital management processes during construction, making it difficult to effectively integrate and promote digital practices at the construction stage at the top-level design level.

Although specific steps have been proposed for the reverse implementation of BIM technology, in practical operations, the complexity and diversity of different infrastructures, coupled with the absence of unified modeling standards and data management norms, make it difficult to guarantee the efficiency and quality of reverse modeling. Furthermore, imperfect data interaction and collaborative work mechanisms with other stages prevent the formation of a full-lifecycle digital closed-loop management, thereby affecting the integrity of the top-level architecture design.

Despite the concept of Mobility as a Service (MaaS) being proposed, it faces numerous challenges in practical applications, such as fragmented information, decentralized infrastructure, and operational imbalances. This reflects a lack of overall planning and guidance at the top-level design level for the integration of mobility services with the digitization of road infrastructure. Consequently, traffic resources and services have not been effectively integrated, leading to an imbalance between user demand and transport supply. This, in turn, constrains the orderly development of the digitization of new road infrastructure.

In each stage of road infrastructure digitization, there exists a phenomenon of fragmentation, with a lack of unified top-level guidance and standardized design. It is urgent to strengthen top-level planning and coordination to promote the efficient and orderly advancement of the digitization of new road infrastructure.

4. Conclusion

As the digital economy expands and new technologies advance, the construction of digital road infrastructure is constantly being refined and enhanced. However, its technical and economic attributes, as well as its development patterns, still require thorough examination. This paper zeros in on the business application layer within the technical framework of digital road infrastructure systems. It starts by outlining the vast scale of China's transportation infrastructure and the context of its digital transformation. Following that, it delves into the innovative practices employed at different stages, encompassing various design approaches in survey and design, effective strategies in construction management, BIM applications in operation and maintenance, and the incorporation of MaaS systems in travel services. Yet, the industry faces hurdles such as a nascent technical system and an absence of top-level design. Hence, it is imperative to bolster the integration of technological research and development, strengthen top-level planning and coordination, and optimize application services. By doing so, we can ensure orderly and efficient development, propel the modernization of the transportation industry, and fortify the foundation for the innovative development of the national economy and society.

Acknowledgements

This research was funded by Research on the critical technologies of the underlying digitization of transportation infrastructure(2023-A-10).

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