The Theory and Application of Digital Twin Technology in the Whole Life Cycle Management of Intelligent Water Conservancy Project

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Abstract: In order to solve data fragmentation problems, lagging management and control, and empirical decision-making in the whole life cycle management of traditional water conservancy projects, and to meet the development requirements of the Ministry of Water Resources for the intelligent full coverage of medium-sized and above reservoirs in 2025, this paper carries out the deep integration research of digital twin technology and the whole life cycle management of water conservancy projects. Firstly, an integrated theoretical framework is constructed to clarify the core orientation of intelligent management and control and the coordination logic of the whole process. Secondly, a phased digital twin model is established, which covers the GIS + MIKE21 coupling model in the planning stage, the BIM refinement model in the construction stage, the BIM / GIS fusion intelligent simulation model in the operation and maintenance stage, and the whole life cycle data fusion model in the decommissioning stage. Finally, a data collaboration platform with five-level architecture of ' perception-network-data-service-application ' is built, which integrates four core functions of data monitoring, model management, intelligent decision-making and cross-subject collaboration. Through the practical cases of Guanzhuang Reservoir and Weishan Irrigation District, the scheme can effectively improve the accuracy and efficiency.

Keywords: Digital Twin; Water Conservancy; Life Cycle Management; Smart Water Conservancy; Collaborative Platform
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1 Introduction

With the acceleration of China's intelligent water conservancy construction, the Ministry of Water Resources has clearly put forward the goal of achieving full coverage of medium-sized and above reservoirs by the end of 2025 [1]. However, in the traditional life cycle management mode of water conservancy projects, problems such as data fragmentation and lagging management and control are particularly prominent. In this context, digital twin technology provides new ideas and technical support for solving the above management problems by virtue of the core characteristics of virtual-real mapping, real-time interaction and intelligent decision-making [2].

By constructing the theoretical system of the whole life cycle management of water conservancy projects driven by digital twin, this paper can further improve the theoretical framework of the field of intelligent water conservancy, and in practice, put forward the technical application scheme that can be implemented, which can effectively improve the accuracy and efficiency of the whole process management of water conservancy projects, reduce the construction and operation cost of the whole life cycle, and provide practical support for the intelligent transformation of medium-sized reservoirs in China.

2 Related Theories and Literature Review

As a systematic mode throughout planning and design, construction, operation and maintenance scheduling, and decommissioning disposal, the whole life cycle management of water conservancy projects requires data, intelligence and collaboration [3]. Based on the non-dominated sorting genetic algorithm, Di Zhu et al. proposed a multi-objective optimization method to construct a joint scheduling optimization model of water conservancy projects covering water quality, water quantity, and hydropower and applied it to 13 water conservancy projects in the Hanjiang River.Compared with the standard operation strategy, the total nitrogen and phosphorus concentration is reduced by 36.7 %, the remaining storage capacity is increased by 33.1 %, and the hydropower output is increased by 41.0 %, which provides scientific support for the improvement of water environment and sustainable management of water resources in large river systems [4]. Zhengjie Zhan et al. constructed a TCSE multi-objective optimization model covering time-cost-safety-carbon emissions based on multi-objective optimization theory. By comparing the NSGA-II and NSGA-III algorithms, the significant advantages were verified, and the entropy weight-VIKOR method was used to select the optimal solution from the Pareto solution set [5].

Digital twin technology is the core support of intelligent management of water conservancy projects. Scholars have achieved remarkable results in technology adaptation and model construction [6]. Wengang Li et al. systematically discussed the concept and development process of digital twin intelligent water conservancy and its difference from traditional water conservancy models. They proposed a five-dimensional model of digital twin intelligent water conservancy, summarized the research progress from six aspects of data perception, transmission, analysis and processing, analyzed the application challenges and prospected the development trend of technology, so as to provide reference and guidance for the research of digital twin technology in the field of intelligent water conservancy [7]. Dong Sheng et al. investigated the national legislation and pilot implementation of China 's digital twin river basins and water conservancy projects from eight aspects of design, policy and technology, and used Bayesian network to analyze its reliability. They pointed out that the system architecture and business management design were reasonable, but there were problems such as imperfect policies and regulations, insufficient investment and personnel guarantee mechanisms, etc., which provided reference for the redesign of water conservancy projects and river basin management under the global digital twin scheme[8].

In order to quantitatively evaluate the application effect, the existing research has formed a multi-dimensional evaluation system, which has gradually expanded from the core dimensions of quality, efficiency and safety to the dimensions of cost and synergy[9]. In general, although the existing research has made significant progress, there are still some problems, such as the lack of integrated modeling of the whole life cycle and simulation accuracy of extreme scenes [10], which leaves room for optimization for this study.

3 The Life Cycle Management Theoretical Framework and Model Construction

3.1 Theoretical Framework Design

Combined with the digital twin technology and actual needs, this paper builds an integrated theoretical framework. With intelligent management and control as the core, covering the whole process, using technology to build strong support, and relying on the security system to escort, a set of non-breakpoint, fully coordinated life cycle management mode is formed.

Table 1. The Core Component of Theoretical Framework of Whole Life Cycle Management

Framework Composition	Specific Content	Core Role
Core Objectives	Intelligent full-process management and control of water conservancy projects; realizing precise planning, refined construction, intelligent operation and maintenance, and rational decommissioning.	Clarify the management direction and guide the design and implementation of the entire framework.
Key Links	Planning and design, construction, operation and maintenance scheduling, decommissioning disposal (fully covering the whole life cycle of the project).	Smooth the management process and ensure seamless connection and no management breakpoints in all stages.
Technical Support	Data perception technology, digital modeling technology, data governance technology, virtual-real interaction technology, intelligent decision-making technology.	Provide core technical guarantee to support the implementation of the framework and intelligent management and control.
Guarantee System	Standard specification system, data security system, talent training system.	Provide all-round support to ensure the orderly advancement of technology application and management implementation.

3.2 The Integration Path

The digital twin technology is closely integrated with all aspects of the whole life cycle of water conservancy projects, and a targeted landing scheme is constructed in combination with the characteristics of engineering types. The design of Weishan Irrigation District in Liaocheng City, Shandong Province has a certain scale. The irrigation area is 5.18 million mu, accounting for 65 % of the total cultivated land area in Liaocheng. It undertakes the task of inter-basin water diversion from the Yellow River to Hebei, and the cumulative water supply exceeds 61 billion cubic meters. ' 1 + 3 + N ' system formed by digital twin construction has a very high reference value as a full life cycle integrated application in irrigation areas.

In the planning and design process, Weishan Irrigation District is in the digital twin planning stage. Based on the physical project, the multiple needs of irrigation water supply, inter-basin water transfer, flood and drought disaster prevention and control are considered as a whole, and the integrated perception system of 'sky-ground-hydropower' covering the whole irrigation area is constructed. Satellite remote sensing, more than 2000 monitoring sites, more than 1100 high-definition video surveillance and other sensing equipment are integrated, and the long-term sequence observation data such as meteorology, water and carbon flux and crop yield accumulated in the irrigation area for more than 20 years are synchronously accessed. Through the integration of future meteorological data processing, MODIS satellite remote sensing data real-time assimilation and other technologies, a multi-scale water demand prediction model is established to promote the transformation of planning and design from 'empirical judgment' to 'data-driven', and greatly improve the matching degree between planning and actual operation.

In the construction process, the main intelligent control is to strengthen the dynamic coordination of engineering construction and digital model. In the construction process of Weishan Irrigation District, the construction of digital twin platform and the construction of physical engineering are promoted synchronously. 247 kilometers of optical cables are laid along the backbone channels, and 28 automatic flow measurement facilities, 1182 hydrological monitoring stations, 11 main canal control gates and 50 branch canal gates are deployed to realize the synchronous installation and debugging of sensing equipment and physical engineering during the construction process. Based on BIM + GIS fusion modeling technology, the digital twin of irrigation area project is constructed, and the 264 km channel, more than 800 buildings and 46,300 mu of embankment confirmation information are accurately mapped to form a management mode of 'one map of irrigation area', so as to realize the visual control and precise control of engineering construction layout and ownership boundary.

In terms of water resources scheduling, based on the optimized water distribution scheduling model and hydrodynamic simulation model, combined with prediction data, the exclusive water distribution scheme for the irrigation season is generated, and the water flow process is previewed and simulated through the digital twin interface to verify the feasibility of the scheme and dynamically adjust, completely avoiding the limitations of traditional experience scheduling. The core data such as the Yellow River incoming water and key stations data are synchronized in real time to the plane generalization map. During the spring irrigation period, the irrigation demand of more than 1 million mu of soil moisture-deficient farmland was successfully guaranteed, and the irrigation cost of large grain growers was reduced by more than 30 yuan per mu. In the aspect of project operation and maintenance supervision, the intelligent patrol channel scene is constructed, and high-definition video surveillance, drones, special vehicles for project inspection and other means are integrated to monitor the water supply status of the channel 24 hours a day. Through the Dayuzhen integrated equipment, the AI intelligent identification of channel water level, gate opening, water surface floating objects and other indicators is realized, and the abnormal information is automatically screened and warned, which greatly improves the efficiency of problem disposal.

In the decommissioning stage, the digital twin construction of Weishan Irrigation District can integrate the full-cycle data of project planning, construction, operation and maintenance through digital twins, including equipment operation life, fault record, structural safety monitoring data, etc., to build a simulation model for decommissioning assessment, accurately predict the remaining service life of buildings such as channels and gates, and evaluate the environmental impact and economic costs of different decommissioning schemes.

3.3 The Whole Life Cycle Model Construction

In the planning stage, the GIS + MIKE21 coupling technology is used to construct the hydrological-engineering coupling digital model of the basin, and the engineering stress and hydrological response under the condition of once-in-a-century flood are simulated. In the construction stage, the construction refinement model is constructed based on BIM technology, and the IoT monitoring data is integrated to realize the real-time update and dynamic calibration of the model, so as to accurately control the construction progress and quality. In the operation and maintenance stage, BIM / GIS fusion modeling and intelligent simulation technology are used to integrate real-time monitoring data and historical operation and maintenance data, so as to realize the dynamic evaluation and accurate scheduling of engineering operation status. The whole life cycle data fusion model is constructed, and the decommissioning disposal scheme is optimized by combining the demolition simulation technology.

Each stage adopts unified data format and interface standard to realize seamless connection and data connection, and provides a unified digital carrier for the whole process management. Guanzhuang Reservoir Management Bureau draws on the advanced experience of Lusong District River and Lake 3.0 system. The system integrates UAV river patrol, unmanned survey ship, 3D river and lake archives and other technologies to achieve fine water control and intelligent river management through four scenarios such as ' air river chief ' and ' online river chief '. The two sides will conduct in-depth exchanges around information data integration and sharing, digital twin and other contents.

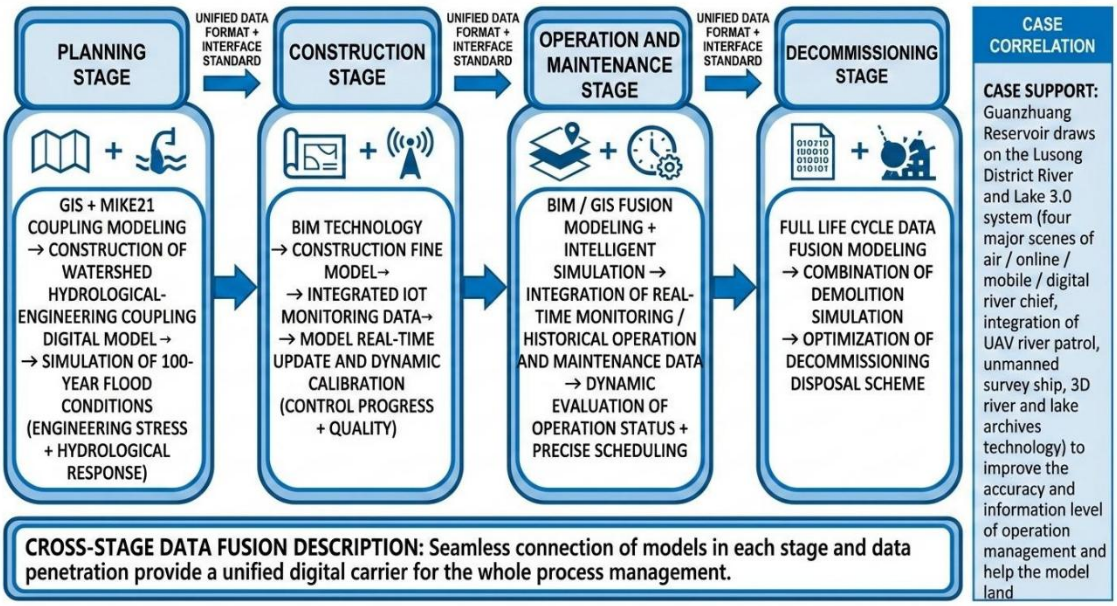

Figure 1. The Whole Life Cycle Model Construction

4 Building Data Collaboration Platform

The platform is built around 'data governance-model operation-collaborative decision'.

1.Data monitoring function : Real-time access to multi-source data in the perception layer, display real-time data and changing trends of core indicators such as hydrology, engineering, and environment through a visual dashboard, and support automatic alarm of abnormal data.

2. Model management function : realize the unified management of the whole life cycle digital twin model, support the upload, update and simulation operation of the GIS + MIKE21 coupling model in the planning stage and the BIM model in the construction stage, and realize the seamless connection and data connection of the models in each stage through the unified data format and interface standard.

3.Intelligent decision-making function : Based on the high-quality data after data layer governance, the decision-making suggestions such as planning scheme evaluation report, construction schedule deviation analysis and operation and maintenance scheduling scheme are generated through the intelligent decision-making service module. In the fault warning scenario, the fault early warning is realized by real-time analysis of the equipment operation data.

4.Cross-agent collaboration function : build a multi-agent collaborative interaction module, support water conservancy management departments, construction units, operation and maintenance units and other cross-agent permissions hierarchical management and data sharing, to achieve real-time synchronization and collaborative approval of planning, construction progress, operation and maintenance records and other information.

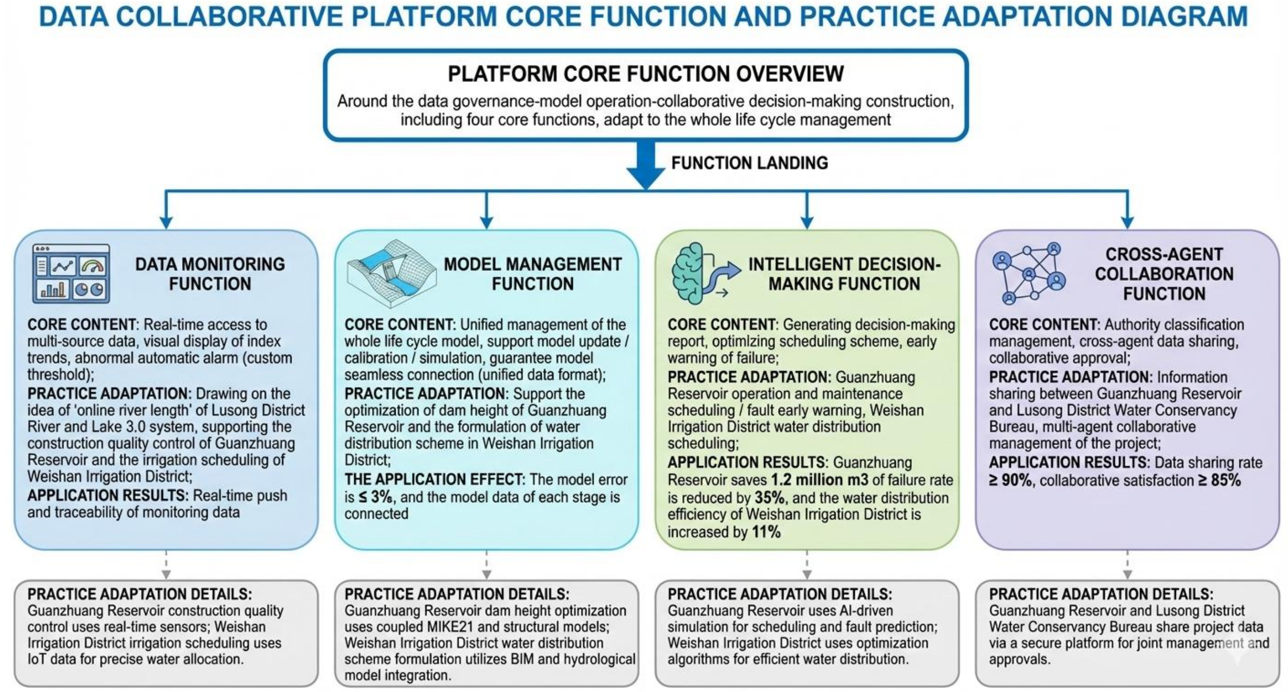

Figure 2. Schematic Diagram of Data Collaboration

5 Conclusion and Prospect

This paper focuses on the integration of digital twin technology and the whole life cycle management of water conservancy projects, constructs the theoretical framework, establishes a phased digital twin model, builds a data collaboration platform with four core functions, and verifies the effectiveness of the technology and scheme through the practical cases of Guanzhuang Reservoir and Weishan Irrigation District. At the same time, the research still has the shortcomings of insufficient simulation accuracy of digital twin model in extreme hydrological scenarios and the need to improve the lightweight adaptability of data collaboration platform. In the future, the numerical simulation algorithm of extreme scenarios can be further optimized, the lightweight application of mobile terminals can be developed, the application of technology in multiple water conservancy projects such as irrigation areas and embankments can be expanded, and the long-term cost-benefit evaluation system of digital twin technology application can be improved.

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