Proceedings of the 4th International Conference on Functional Materials and Civil Engineering
DOI: 10.54254/2755-2721/2026.38395

Systems and Strategies for Refined Management over the Full Life Cycle of Water Conservancy Projects

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Abstract. Water conservancy projects are key national engineering facilities, and their construction quality and operation have direct impact on regional economic and social development. However, traditional management mostly focuses on the construction stage but pays insufficient attention to planning, design, operation and maintenance stages, resulting in data discontinuity and delayed decision-making. This paper analyzes the connotation of full life cycle management and refined management from a system perspective. It studies the main barriers to realization of full life cycle refined management from the perspectives of technical obstacles (incompatible data systems and weak automated diagnosis), management mechanism problems (capability gap and fragmentation of activities), and imperfect policies or standards. Four enabling technologies are then discussed, namely building information modeling (BIM), intelligent monitoring based on the Internet of Things (IoT), big data analysis and prediction, and smart management platforms based on digital twin concepts. Finally, development suggestions are put forward, including establishment of a full life cycle refined management framework with maturity assessment and collaborative learning, and improvement of specialized and lightweight standards accompanied by incentive mechanisms. The findings provide a reference for the transformation of water conservancy project management modes.

Keywords: water conservancy project, full life cycle management, refined management, digital twin, Internet of Things

1. Introduction

Water conservancy projects are among the most important infrastructures in China's socio-economic system, and their construction quality and operation have great influence on the stable development of regional economies and societies. In recent years, many studies on construction safety of water conservancy projects have shown that with increasing scale and technicality of engineering constructions, the uncertainties of risks in construction can't be handled by the conventional risk assessment methods, especially the impact from the complicated geological conditions and multi-source risks seriously affects on-site construction safety, which suggests the defects of the traditional management mode that pays too much attention to construction stage but not enough for preliminary planning & design and later operation & maintenance [1].

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DOI: 10.54254/2755-2721/2026.38395

During operation and maintenance, inefficient information transfer also limits management performance. For example, water leakage detection in a water distribution network remains challenged by its complex acoustic environment and lack of automated diagnostic capability; conventional machine learning models only output binary labels but cannot trace back to diagnose where the problem lies [2]. In the water resource system of the Fen River Basin in Shanxi Province, China, hydrometeorological, socioeconomic and engineering regulation links intertwine and collectively affect system resilience—without cross-stage systems thinking, optimizing a single stage is unlikely to result in improved overall performance [3].

Chinese scholars have also done some work on the effect of refined management. Taking typical water conservancy projects in Jiangsu Province as an example, a 52-indicator system including architecture, operation and effectiveness was set up to explore the effectiveness of refined management, which shows that the mean value of qualitative indicators accounts for 79.169% of the total evaluation value, and the comprehensive evaluation value of quantitative indicators reaches 94.995%, which demonstrates that refined management can improve the integrity and safe operation rate of water conservancy projects effectively [4]. But these practices are mostly based on pilot projects of single reservoirs or irrigation districts, and a standardized one can be widely promoted is still lacking.

To solve these problems, the Ministry of Water Resources of the People's Republic of China has issued a number of policy documents in recent years. The key requirements can be roughly summarized as follows. First, the "four comprehensives," "four systems," "four forecasts" and "four managements" are required for modernized reservoir operation and management. Second, reservoir management should move toward digital, intelligent and collaborative transformation [5]. Third, digital twin technology should be incorporated into the full life cycle management of hydropower projects, integrating data from planning, site selection, construction, operation and maintenance to safety emergency response, and continuously calibrating the model so as to provide a technical route for the industry [6].

It is worth noting that although the concept of life cycle management (LCM) has received widespread theoretical attention, its practice faces technical, institutional and policy obstacles [5, 6]. Few studies have conducted a systematic review of the LCM system and strategy of refined management from one or more stages. At present, most of the relevant research mainly focuses on technical optimization of a single stage. This paper takes the LCM system of water conservancy projects as an example, systematically analyzes the applicability of LCM, reviews the connotation and key challenges of full life cycle refined management, elaborates the application logic of BIM, IoT, big data analysis and smart management platform as the main four management means of LCM, and proposes corresponding implementation suggestions, which provides a reference for the transformation of water conservancy project management modes.

2. Connotation of full life cycle refined management

2.1. Connotation of full life cycle management

Full life cycle management refers to a management mode covering the whole process of a project, including planning and site selection, survey and design, construction, operation, maintenance and even decommissioning [6, 7]. In this mode, every stage is connected organically and continuously so as to avoid discontinuous data or delayed decisions in fragmented stages. According to the International Organization for Standardization (ISO) 15686-1:2011, one of the most important principles of full life cycle management is that "the system approach should be applied to ensure

DOI: 10.54254/2755-2721/2026.38395

that assets are planned with respect to their function, economy and environment throughout their whole life cycle" [7].

From a systems theory perspective, full life cycle management of water conservancy projects covers four core stages: at the planning stage, spatial intelligent comparison and selection are carried out with comprehensive consideration of topography and ecological constraints; at the design stage, multi-scheme collaborative optimization is realized through the integration of BIM and geographic information system (GIS); at the construction stage, decentralized control of schedule, quality, safety, cost, and other elements poses difficulties; and at the operation and maintenance stage, the continuous safety of units and hydraulic structures must be ensured [6]. The goal of full life cycle management is not only to complete the tasks of each stage, but also to guarantee the functional resilience of engineering systems when facing extreme events [8, 9].

2.2. Connotation of refined management

Refined management comes from the development trend of "accuracy, standardization, and traceability" in modern management theory. The introduction of refined management into the full life cycle management will refine the management object from a project as a whole to components and working procedures. The connotation of full life cycle refined management for water conservancy projects shows multidimensional characteristics of systematicness, continuity, and intelligence. "Systematicness" means that all management activities in each stage should form a closed loop with each other under the guidance of a unified data base and standard system, which reaches the level of full-process coordination from flood control dispatching to ecological security [5]. "Continuity" means that information should be transferred continuously along the time axis. Predictive maintenance at the operation stage is possible only if historical operation data are accumulated and shared [2, 6]. Intelligence is embodied in the deep integration of BIM, IoT and big data analysis, management objects to detailed elements and procedures, realizing dynamic perception and intelligent early warning [1, 6].

Chinese scholars have done some empirical exploration on the effectiveness of refined management. For example, Jiangsu Province took some typical water conservancy projects as research objects to construct a 52-indicator refined management evaluation system including architecture, operation and effectiveness, and found that the mean value of qualitative indicators accounted for 79.169% of the total evaluation value, while the comprehensive evaluation value of quantitative indicators reached 94.995%, which indicated that refined management improved the integrity rate and safe operation rate of the water conservancy projects [4]. There is still a lack of practices at the level of a standardized, wider promotion. Most of the practices are based on pilot projects of single reservoirs or irrigation districts, and its adaptability to small and medium-sized water conservancy projects needs to be verified [4, 5].

In summary, full life cycle refined management of water conservancy projects is a comprehensive subject integrating systems engineering, information technology, and modern management theory. Its successful implementation depends not only on the advancement of individual technologies, but also on the continuity of data across all stages, the optimization of management mechanisms, and the supporting improvement of policies and standards.

DOI: 10.54254/2755-2721/2026.38395

3. Challenges facing full life cycle refined management of water conservancy projects

3.1. Technical barriers

The core technical contradiction lies in the fact that data are scattered in different systems without interoperability mechanisms. In a study of water treatment facilities, it was pointed out that knowledge at the design stage is encapsulated in BIM models under the Industry Foundation Classes (IFC) standard, whereas knowledge at the operation stage is deposited in computerized maintenance management systems; the two systems are incompatible, and handover can only rely on manual re-entry, causing a massive loss of the semantic associations between equipment and the original design intent [10]. Quoted industry estimates suggest that the proportion of knowledge lost in the design-to-operation handover can reach 40%–60%. Inconsistent data formats also trouble operating agencies: about 70% of water utilities regard incompatible data formats as the main obstacle to data utilization [10].

Automated diagnostic capability in monitoring is another weakness. For example, leakage detection in water distribution networks suffers from two difficulties at the same time: the complex acoustic environment and insufficient automated diagnosis [2]. For large-scale water conservancy projects, the regulation chain has to be considered as an integrated system due to the intertwining of hydrometeorological and socioeconomic factors, which cannot be supported by isolated analysis of single-point data [3]. International standards are not uniform, either. Although the IFC standard for building applications is relatively mature, there is no extension to water treatment or water conservancy facilities, which causes the model data with different semantics to flow across software and across stages [10].

3.2. Management mechanism issues

Even with the adequate technical conditions, however, outdated management mechanisms can reduce refined management to mere formality. Long-term observations in Sweden have shown that one of the major difficulties is the capability gap between what municipalities need (to recruit more people who can manage an ageing pipe network) and what universities are training (to produce more engineers for new construction than for the operation and management of existing infrastructure); there is not enough practice on condition assessment, risk decision-making and whole life cycle cost accounting [11].

Deeper obstacles lie within organizations. Although many agencies have done some maintenance and inspection planning, some investment strategies, and some data collection, these efforts have not cohered with one another nor been coordinated across departments; investment decisions have not been made on the basis of explicit service levels or long-term goals; risk thinking has not been integrated into decision-making; and financial planning has routinely adopted a short-term budget perspective that ignores the total cost of assets over their whole life cycle [11]. An equally easy-to-overlook but important phenomenon found in the study is how personnel turnover, lack of incentives, and short policy cycles reinforce one another, making it difficult for asset management to be steadily undertaken by organizations as a common strategic function, especially in smaller agencies [11].

DOI: 10.54254/2755-2721/2026.38395

3.3. Imperfect policies and standards

Regarding policies and standards, the problem lies not in their absence but in the mismatch between supply and demand. In recent years, the Ministry of Water Resources has explicitly put forward modernized reservoir operation and management requirements centered on "four comprehensives" and "four forecasts" [5]. Digital twin technology has also been incorporated into the technical route of full life cycle management of hydropower projects [6]. The policy orientation is clear enough; however, between macro requirements and enforceable operational specifications there remains a gap of detailed standards and evaluation tools.

A prominent illustration is the implementation dilemma of international standards in small and medium-sized agencies. In research on Greek small and medium-sized water utilities, the difficulty encountered in implementing ISO 55001 was not whether the standard itself was relevant, but the lack of a lightweight and operable implementation path [11]. Similarly, it has been noted that existing data exchange standards offer insufficient dedicated support for water treatment facilities, and general semantic frameworks can hardly adapt directly to the specialized expression needs of water conservancy equipment [10]. The domestic situation shares similarities: refined management practices are mostly confined to pilot projects of single reservoirs or irrigation districts, a standardized framework for wide promotion has not yet been formed, and the adaptability to small and medium-sized projects in particular remains to be verified [4].

4. Technologies for full life cycle refined management of water conservancy projects

4.1. Application of BIM technology

The value of BIM has gone far beyond 3D visualization. When used for full life cycle management, BIM is a data base that runs through all stages of a project: the model holds the design parameters, spatial relationships and equipment attributes of a building structure—thus providing a unified semantic benchmark for later-stage queries, analyses and decisions [6]. These are exactly the areas where water conservancy projects with their complex components and dense spatial relationships can benefit from BIM.

A typical case is the Water Asset Management Ontology (WAM-ONTO) framework, which connects the IFC4 model with the Web Ontology Language (OWL2) and automatically translates design models into knowledge graphs suitable for machine reasoning [10]. The framework contains 996 ontology classes and 61 object properties; in a field test of the clean-in-place (CIP) system of a water plant in New Zealand, it achieved an automatic classification accuracy of 89% for 2,411 building components and a design knowledge retention rate of 96%, allowing the BIM model to continue almost losslessly through the handover from design to operation [10]. Industry-level benefits are equally considerable: in a quoted case, Severn Trent Water in the United Kingdom achieved cost savings of about five million pounds in the Minworth project with the help of BIM, a reduction of 13.5% [10]. It is worth noting that such practices reveal a common rule: the return on BIM is not limited to the design and construction stages; whether model data can continue into operation determines its full life cycle value.

4.2. Intelligent monitoring and the Internet of Things

BIM provides the data base, while the IoT enables real-time updating of data. By placing sensors at key nodes (pressure, flow, temperature, etc.) in the pipes and linking them with a wireless

DOI: 10.54254/2755-2721/2026.38395

transmission network, the operating status of projects can be fed back in real time to the central control platform for rapid response if any anomaly occurs [12]. As an example, the safety monitoring of building water supply and drainage networks by integrating BIM models with sensor networks to build a real-time monitoring system of the whole pipe network of a building was reported [12]. Experimental data show that the total time (from collecting data to completing system processing) was <30 ms, the alarm response time for simulated pipe burst/sudden pressure rise was 150-200 ms, and the standard deviation of water pressure in a 24-h continuous operation was only 1.1 kPa [12]. Similarly, the same perception logic can be applied to water conservancy projects, including seepage pressure of dams, gate opening and vibration of pumping station units, which can also be monitored by IoT technology. To meet the intelligent diagnostic demand on leak detection, Liu et al. further introduced retrieval-augmented large language models to supply traceable diagnostic context for acoustic leak detection [2]. Monitoring alone does not automatically bring management improvement. Massive real-time data can only become a basis for decision-making if appropriate analytical methods are applied, which is the topic of the next section.

4.3. Big data analysis and prediction

The value of big data analysis lies in identifying patterns that are difficult for human judgment to detect from monitoring data and in predicting operating conditions. Typical applications of such technologies in the operation and maintenance of water conservancy projects include failure probability modeling, identification of critical components, and optimized ranking of maintenance resources.

A complete demonstration is provided by a study based on actual pipe network data of a water supply company in Zhengzhou, where a digital twin model combined with Monte Carlo simulation was used to reproduce complex scenarios of simultaneous leakage and burst of multiple pipes [13]. A "residual resilience importance" indicator considering time value was then proposed to dynamically rank the repair order of failed pipes, and the simulation results show that this dynamic repair strategy reduces the residual resilience value of the network to 0.3013, which is 43.47% and 63.15% lower than static repair strategies and betweenness-centrality-based strategies, respectively, so that repair resources are concentrated on the links with the greatest impact on system performance [13]. In addition to data-driven methods, knowledge-driven reasoning paradigms are also emerging in water conservancy projects. The semantic framework described above has 82 Semantic Web Rule Language (SWRL) rules built in, which can automatically complete equipment classification, risk profiling, and maintenance priority determination: for an analytical task such as identifying "equipment critical to the disinfection process," the system takes less than five seconds, while manual completion usually requires 20 to 30 minutes [10]. It is worth noting that the two paradigms do not replace each other: data-driven methods excel at mining patterns from massive historical data, while knowledge-driven methods guarantee the interpretability of reasoning, and their fusion may be a direction worthy of attention.

4.4. Smart management platforms

The individual technologies introduced above can finally be integrated into a unified platform. The so-called smart management platform (or its simplified form—digital twin) is a carrier of the convergence of various technologies. Usually, it has a typical architecture of four layers from bottom to top: perception layer, data layer (data storage and cleaning), platform layer (modeling, simulation,

DOI: 10.54254/2755-2721/2026.38395

and intelligent decision-making), and application layer (dispatching, early warning, emergency management, etc.) [13].

The effect of this integrated architecture is validated by a digital twin platform case applied to the Zhengzhou pipe network: the platform enables the managers to get an overall view on the network status in real time as well as take preventive actions before failures occur. For example, after installing valves and redundant pipes on some critical pipes, the network's performance was improved by 31.69% and 44.15%, while the losses from network resilience against failure were reduced by 40.20% and 59.41%, respectively [13]. In addition, the platform-based management allows an extension of the management boundary of the asset management system: for instance, the WAM-ONTO framework provides query and reasoning functions via standardized application programming interface (API) interfaces so that the asset management platform can be connected to other management systems like maintenance management systems, and knowledge can be exchanged bidirectionally between them, avoiding duplicated construction [10]. At the domestic policy level, digital twin river basins and smart water conservancy construction have been explicitly listed as directions of industry transformation [5, 6]. Platform integration is becoming an industry trend, and with the maturity of individual technologies, the development focus of smart management platforms is shifting from function stacking to the completeness of data continuity and decision-making closed loops.

5. Suggestions for the development of full life cycle refined management of water conservancy projects

5.1. Establishing a full life cycle refined management framework

Technical means provide possibilities, but turning possibilities into management performance requires supporting frameworks, standards, and policies. Framework establishment needs to clarify management objects and management order. The former points to a unified data base and multidimensional evaluation criteria, while the latter requires a phased and measurable implementation path.

Data continuity is the physical foundation of the framework. As described above, design knowledge and operation knowledge reside in different systems, which is the largest breakpoint of refined management [10]. The framework should take the integrated BIM and GIS model as the unified data base and require deliverables of each stage to carry structured semantics, so that model data are automatically transferred with project handover rather than re-entered manually [6]. On this basis, evaluation dimensions need to go beyond the two traditional indicators of investment and schedule and bring environmental and social benefits onto the same scale. For instance, life cycle assessment (LCA) has been coupled with the Storm Water Management Model (SWMM) to construct a multidimensional sustainability evaluation framework covering five stages—collection, storage, treatment, utilization, and waste disposal—with the analytic hierarchy process used to coordinate environmental, economic, and social indicators [14]. In the case of Wenzhou, this framework quantified that a rainwater utilization system has a global warming potential about 20% lower than that of a traditional water supply system, and identified the comprehensive advantage of rain gardens in the environmental (0.8) and social satisfaction (0.75) dimensions, giving strategy selection a defensible basis [14].

Whether the framework can be implemented depends on whether managers are given a clear path from the current state to the goal. Digital transformation (DT) maturity can be characterized by 56 indicators in seven categories—strategic intent, data, digital talent, organizational processes and

DOI: 10.54254/2755-2721/2026.38395

systems, technology, asset delivery, and asset management—and can be improved level by level along a five-level scale from initial to optimized [15]. The case of an Australian state-owned company shows that most categories are currently at level two, and the organization has set five-year and ten-year graded goals accordingly [15]. Attention should also be paid to indicator weights: in the asset management category, "asset whole life cycle value" ranks first with a weight of 25.4%, significantly higher than the technical indicators in the same category, which suggests that the focus of framework construction should be value management rather than technology stacking. For water conservancy project management units, a self-assessment mechanism can be established along this line of thinking, with maturity levels as coordinates, promoting data continuity, process reengineering, and capacity building by stages. Regarding the capability gap described in Section 3, the relevant experience is also worth drawing on: modular collaborative learning organized around ISO 55000 can help resource-limited agencies build management vocabulary and operating routines at low cost through peer exchange [11].

5.2. Improving the standards and policy system

The focus should be on "specialization" and "lightweighting". Specialization means filling the gap of data standards for water facilities. The existing IFC system lacks sufficient coverage of water treatment and water conservancy equipment, which makes it difficult for general semantic frameworks to express specialized objects directly. Therefore, the industry needs to formulate extension specifications for water conservancy projects based on existing international standards to unify equipment classification, attribute naming and delivery formats [10]. Lightweighting is meant to tackle the implementation dilemma of small and medium-sized agencies. For example, a study of Greek water utilities shows that these small and medium-sized agencies lack not so much the standard text itself as a simplified and more flexible implementation path of ISO 55001 [11]. This judgment also holds domestically: refined management practices remain confined to pilot projects of single reservoirs or irrigation districts, and the adaptability of small and medium-sized projects needs to be verified [4]. Therefore, the standard system should adopt a graded design: large projects benchmark against the complete framework, while small and medium-sized projects are provided with simplified data templates and minimum viable management requirements, avoiding the implementation vacuum caused by "one set of standards for all."

At the policy level, the focus should be on coordinating evaluation tools with incentive mechanisms. On the one hand, maturity assessment can be introduced into industry management to approve DT investment or assess management effectiveness—maturity measurement based on weighted scoring and multi-role perspectives can help organizations set improvement goals and produce short-and long-term recommendations [15]. On the other hand, room should be left for trial and error in promoting technology—for example, emphasize effective communication among managers, industry, and the public so that policymakers can translate evaluation results into policies, and stress the importance of mechanisms such as policy seminars and public education [14].

In line with the digital twin river basin construction direction already clarified in China, mature evaluation frameworks and management tools can be piloted on demonstration projects first and then precipitated into industry norms.

DOI: 10.54254/2755-2721/2026.38395

6. Conclusion and outlook

6.1. Conclusion

Focusing on the theme of "full life cycle refined management" of water conservancy projects, this paper sorted out the connotation of full life cycle refined management of water conservancy projects, analyzed the main obstacles for realizing it, and studied the key technologies. It is concluded that the essence of full life cycle refined management lies in connecting the four stages of project planning, design, construction and operation with a unified data base, refining the management object from projects to components and working procedures, so as to realize accurate, standardized and traceable control. Its implementation obstacles are distributed at three levels: technically, data are scattered in heterogeneous systems and design knowledge is massively lost during handover; institutionally, capability gaps and departmental fragmentation make management activities difficult to coordinate; and in terms of policy, there is a mismatch between standard supply and engineering practice, with the adaptability to small and medium-sized projects particularly insufficient.

At the technical level, BIM as a data base can extend design knowledge into the operation stage; IoT monitoring gives projects real-time perception capability; big data analysis distills patterns from operating data and supports predictive decision-making; and smart management platforms integrate individual technologies into a complete closed loop of perception, analysis, and decision-making. The four are not isolated from one another, but constitute a chain of value increment from data, information, and knowledge to decision-making.

Accordingly, two suggestions are proposed. At the framework level, a management system based on data continuity and centered on whole life cycle value should be established, promoted by stages with the help of maturity models, and the capability gap should be filled through collaborative learning; at the institutional level, standards should be developed in parallel toward specialization and lightweighting, accompanied by maturity assessment and pilot incentive mechanisms, so that macro policies are transformed into enforceable operational specifications.

6.2. Outlook

This review is mainly based on literature analysis, and most cited cases come from water conservancy projects and related infrastructure fields, which still need further verification in more complex scenarios, such as water conservancy hub and river embankment management. The future development trends include data-driven and knowledge-driven fusion to balance prediction accuracy and decision interpretability, resilience management under extreme event scenarios by extending the full life cycle framework to emergency situations, and cost adaptation for small and medium-sized water conservancy projects to make refined management feasible under resource constraints. With the digital twin river basin construction advancing, the conditions for water conservancy project management moving from experience-driven to data and intelligence-driven mode are gradually maturing. The coordinated construction of relevant management frameworks, standards and talents will determine the speed of this transformation.

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