

Reimagining Water Infrastructure Projects: Digital Tools for Enhancing Construction and Asset Management Practices

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ARTICLE INFO	ABSTRACT
Received: 30 Dec 2022 Accepted: 24 Jan 2023	The process of preparing water infrastructure for the future is increasingly complicated by demographic shifts, climate change, deteriorating infrastructure and the need for secure, sustainable solutions. Conventional project delivery approaches typically struggle to overcome the complex coordination and data silos, as well as lifecycle inefficiencies, associated with infrastructure mega-projects. This paper explores the tactical deployment of Digital Twin (DT) systems within the planning and construction phases of water infrastructure projects. A rigorous methodology is presented that integrates Building Information Modeling (BIM) data with Geographic Information Systems (GIS), Internet of Things (IoT) sensors, and advanced analytics to generate dynamic, interoperable digital reproductions of physical assets. Ensure project design intent is aligned with physical site conditions and construction sequences so plan and design for sustainable use during the asset life cycle. Empirical experiences are gained through the analysis of international case studies and a prototype experimentation that shows concrete benefits such as predictive risk mitigation, enhanced stakeholders coordination and lower operational costs. The results confirm this view that early DT usage brings about compounded processes to become streamlined, data-base processes with ongoing optimization in the asset life cycle. This paper also discusses major challenges to implementation, including issues of data sharing and interoperability, workforce training needs, and cybersecurity, and it provides specific recommendations for the successful adoption of AI into both public and private sector water systems. Keywords: Digital Twin, Water Infrastructure, Early-Stage Planning, Construction Management, Asset Lifecycle Optimization

1. Introduction

1.1. The Evolving Landscape of Water Infrastructure

Water The Importance of Sustainable Public Water Infrastructure on Public Health, Economic Development and Environmental Sustainability Water infrastructure serves as a building block in the United States' public health, economic, and environmental systems. Yet today's systems face increasing challenges as urbanization is occurring at an unprecedented pace, climate patterns are changing rapidly, assets are aging, and regulatory environments are becoming more complex. Outmoded methods for planning and deploying water infrastructure projects – which involve siloed data environments, fragmented decision-making and reactive operations – are no longer sufficient. These constraints lead to ineffective cross-stakeholder coordination, suboptimal resource application, and a suboptimal long-term performance of the asset.

An emerging shift in paradigm is required - one that embeds data-enabled, integrated and predictive tools in the initial stages of the infrastructure life cycle. The impetus to improve design accuracy, increase the speed of project delivery, and build resilience is driving the momentum of digital transformation in the construction and utilities industries.

1.2. Digital Twins: A New Paradigm in Infrastructure Engineering

Central to this shift is the development of Digital Twin (DT) technology. A digital twin is a living, learning system able to learn and update based on real-time data from sensors, models, and other external data sources. Within the scope of water infrastructure, a DT integrates data from Building Information Modeling (BIM), Geographic Information Systems (GIS), Internet of Things (IoT) sensors, Supervisory Control and Data Acquisition (SCADA) systems, and simulation engines, to enable monitoring and optimize performance throughout the asset lifecycle.

Through the reproduction of any physical system within a digital environment, DTs offer a valuable tool for drivers of simulation, predictive analytics, anomaly detection and cross-functional communication.

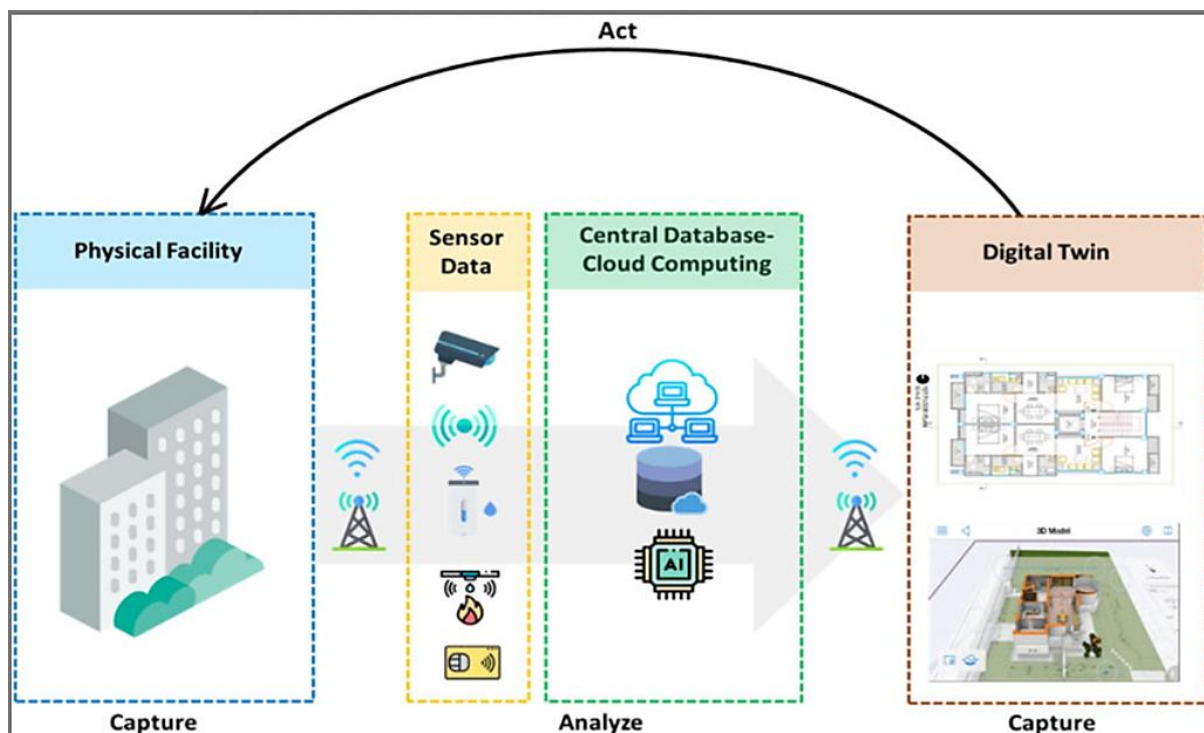


Figure 1: Conceptual framework for Digital Twin integration in construction and water infrastructure projects. (Source: ResearchGate)

As depicted in Figure 1, the DT implementation framework is comprised of four interacting layers: data acquisition, modeling and synchronization, simulation and control, and operational integration. These layers interconnect in a feedback loop that allows for dynamic updates, better decision-making, and an optimized end-to-end lifecycle of water assets.

1.3. The Case for Early-Stage Digital Twin Integration

The majority of the work on DTs to date, are mainly concerned with operational or maintenance phase of the infrastructure. Yet this strategy overlooks a critical opportunity: the early planning and design phase. By incorporating DTs at this point in the process, project teams are able to represent how the design will react in the real world under various conditions, far ahead of when the design actually exists, allowing time to visualize the outcomes and to proactively contending with design clashes or inefficiencies.

For example, with hydraulic modeling and flood simulation in a DT context, it is possible for planners to evaluate how various infrastructure would perform in future climate scenarios. Likewise, early

integration with GIS allows planning and impact assessments to be conducted with more appropriate spatial resolution.

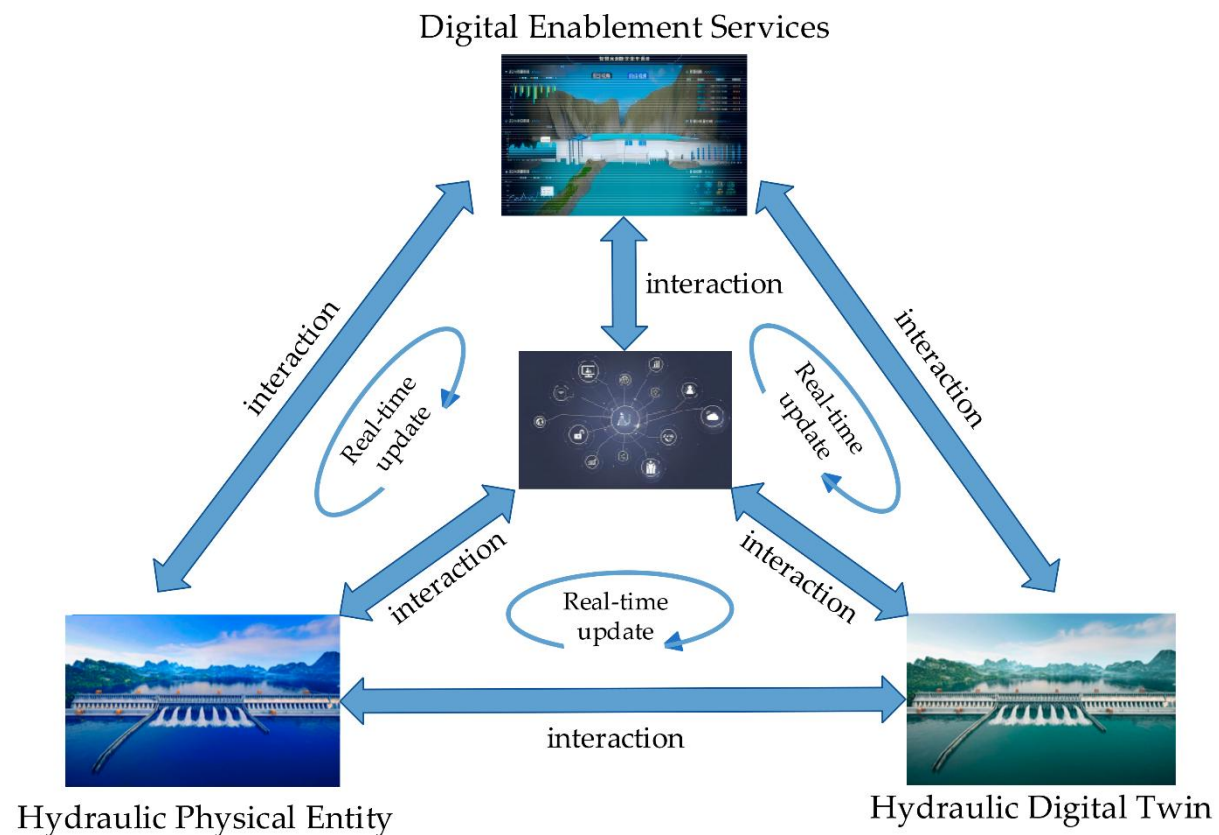


Figure 2: Layered architecture of a smart water system digital twin. (Source: MDPI)

As depicted in Fig. 2, the DT model not only enables asset visualization but also renders real-time integration with water quality sensors, flow meters and remote telemetry units. Such an approach results in a more predictive (as opposed to reactive) way of managing water infrastructure — a game changer.

1.4. Challenges in Traditional Project Delivery

Traditionally, water works project suffers from the lack of information continuity between different stages. Valuable data is frequently not transferred during the transition from design to construction or from construction to operation. This has the effect that the systems operations teams are left with as-built models that are not complete or correct, resulting in maintenance issues and higher lifecycle costs.

Early-stage DT-integration solves this by becoming a single source of truth – a living and breathing model that develops as the physical asset does. Sequences, machinery, pipes and structures are live built with real time simulation for every participant. This method helps minimize the need for rework and ensures smoother handovers and continuous optimization.

1.5. Contribution and Structure of the Paper

This paper provides a conceptual approach and appropriate applications for using Digital Twin systems at the early stage of planning and construction of water infrastructure. It explores how DTs can narrow the divide between design intention and actual construction and how they lay the groundwork for intelligent, climate-resilient infrastructure management.

Based on a synthesis of case studies, prototype analysis and industry interviews, the paper illustrates the hard benefits that can be achieved through early adoption—lower levels of design errors, improved coordination with stakeholders, enhanced control over costs, and greater resilience across the lifecycle. It also identifies inhibitors to adoption including concerns around interoperability, lack of digital skills in the workforce, and cyber security fears.

The remainder of the paper is structured as follows:

- **Section 2** reviews related literature and current limitations in water infrastructure delivery.
- **Section 3** outlines the research methodology and data sources.
- **Section 4** proposes a Digital Twin integration framework tailored to early-phase applications.
- **Section 5** presents case studies and results from simulation-based validation.
- **Section 6** discusses challenges, implications, and strategic recommendations.
- **Section 7** concludes with future directions and policy insights.

2. Literature Review

2.1 Traditional Challenges in Water Infrastructure

Water infrastructure projects have long been dogged by a series of systemic issues in planning, delivery and operation. These projects are typically complicated, capital-intensive, and long-duration in nature, and thus are especially susceptible to coordination failures and inefficiencies [1]. One of the most disturbing forms of fragmentation is separation of the planning, designing, construction, and maintaining processes and teams, many of which work with independent sets of data and purposes [2]. Such disconnected workflow inhibits communication and results in inconsistent execution [3].

It also has a concern of aging infrastructure, pipeline, treatment plant, and distribution network are older than they are being replaced [4]. The absence of operations monitoring leads to a slow and reactive response to new issues during the construction and early stages of operations [5]. This results in cost overruns, schedule delays and performance short falls. Too often, the point at which data is available for decision making is after the opportunity for cost-effective intervention has ended [6]. These restrictions emphasize the necessity for project phases to be aggregated by a tool which is single. to improve data transparency and minutely manage proactive [7].

2.2 Emergence of Digital Twins in Civil Infrastructure

Digital Twins, originating in industrial manufacturing, have been widely studied in civil infrastructure, due to increasing digitalisation of the built environment [8]. A digital twin is not just a visual model, but a living mechanism that is evolving and reflects the real-time physical condition of an asset [9]. For infrastructure works this could entail the production of a real-time digital twin that is able to receive live feeds of data from sensor arrays, simulations, and corporate models (BIM and GIS e.g.) [10].

DTs allow a shift of perspective between a reactive and a predictive management. It helps decision makers prepare for failures, optimize operations, and react to the current conditions (referred to as real-time data analytics) [11]. In civil infrastructure domain, DTs enable a variety of tasks such as scheduling and safety management on construction sites, building energy and environmental monitoring [12]. They have been implemented and have demonstrated benefits by improving asset availability, minimizing downtimes and adding to the transparency of complex projects [13].

2.3 Gaps in Early-Stage Integration

Despite the rise in prominence, the most digital twin efforts in infrastructure to date focus in the postconstruction or operational stages [14]. DTs are often retrofitted after the NFT for the physical asset has already been established, and serve as the primary source of tracking, maintenance and lifecycle optimization. Although this creates great value, it neglected the most significant part of integration in the early stage—where decisions about layout, material and system designs, and coordination with stakeholders are all made [15].

Design and planning are a leveraged opportunity in the life of a project. Errors or inefficiencies added at this stage reverberate through construction and operations, magnifying costs and risks. However, the use of DTs in the conceptual design, feasibility study and early planning phase is still lacking. This is because of the absence of standardization, the integration tools and awareness of stakeholders about the potential of DTs in upstream.

Bringing DTs in at this early level is transformative. It gives planners the ability to model various design options, evaluate the performance of their building in different environmental conditions and, optimize their construction logistics pre-ground breaking. As well, ability to envision infrastructure performance under future scenarios (e.g., developmental pressures, climate stress) offers strategic insight to harmonize project objectives with long-term resilience and sustainability. Filling this gap is important to fully leveraging the potential of Digital Twin technologies throughout the infrastructure lifecycle.

3. Methodology

The study uses a qualitative-quantitative research approach to investigate the decision-making process of implementing Digital Twin (DT) in (early phase) water infrastructure development. The method consists of three major elements which are case study analysis, simulation modelling and stakeholder interviews. Collectively, these factors contribute to an understanding of the technical, operational and organizational dimensions of DT implementation.

3.1 Case Study Analysis

The first phase of the research was the deep-dive study of three global water infrastructure projects that intended to bring the Digital Twin in some capacity. These initiatives were chosen for their geographic, project size and digital maturity diversity. Based on open source reports, technical papers and project documentations document analysis was conducted. The objective was to understand how DTs were implemented in the early stages, the tools and data standards used as well as what the “measurable” benefits were, in construction and handover. Patterns of digital adoption The comparative analysis assisted to determine common consideration points, integration difficulties, and success factors which led to the creation of the study conceptual framework.

3.2 Simulation Modeling

To quantify the potential impact of early DT integration, a prototype simulation model was constructed. A mid-scale water distribution project was modeled and BIM was treated as the bottom layer of the proposed model. Live and replay data streams were emulated with Internet of Things (IoT) sensor inputs which correspond to soil stability, pipe strain, water flow, and power consumption values. The DT concept allowed for testing virtual clones of alternative design concepts, construction schedules and risks. With the model analysed parameters such as project delay, material waste, energy utilisation under various DT -driven decision-making scenarios. The findings offered the empirical evidence that the early development of DT brings a high level of construction execution and readiness of unutilized construction assets.

3.3 Stakeholder Interviews

The third part of the method consisted of semi-structured interviews with 22 interviewees, consisting of civil engineers, digital planners, BIM experts, and facility managers working in five large utility firms that spanned across three continents (Asia, Europe, and North America). Interview topics included current systemic practices in planning and construction, barriers to implementation of DT, data interoperability, and cross-phase collaboration. Common standpoint, resistance points and blacks in knowledge were extracted in views, which were coded thematically by qualitative data analysis software. Results of interviews were further validated with case study findings and simulations, allowing for triangulation and enhancing the study's conclusions.

4. Digital Twin Integration Framework

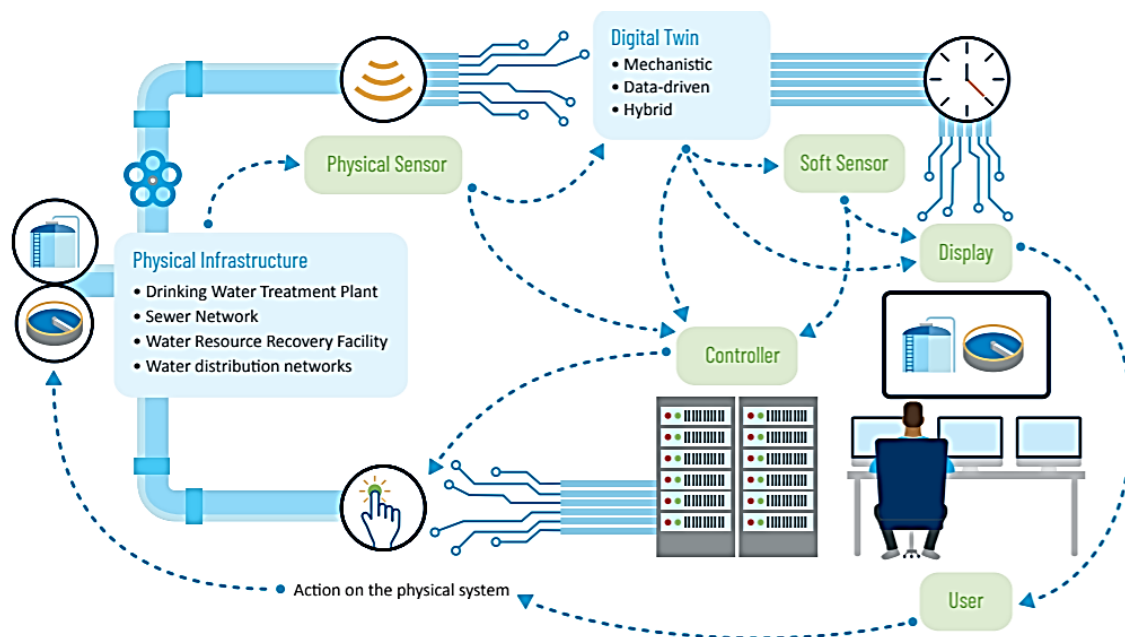


Figure 1: Architecture of a Digital Twin application in the water sector, including real-time operational integration and stakeholder decision support

(Source: IWA Digital Water Programme)

4.1 Framework Components

The bottom-most layer, Data Acquisition, collects real-world data from different sources (eg: LiDAR scans, GIS spatial data, IoT sensors, Telemetry, and Archived legacy data). This unified dataset enables the digital twin to be firmly anchored in reality as it is created: there is no fidelity or continuity gap between the digital and physical realities of the infrastructure.

The Modeling Layer is then established, over BIM which constitutes the mainframe. BIM is the principle tool used to capture geometric, architectural and functional design aspects, and then augmented with hydrological models, system metadata and GIS overlays to achieve a comprehensive virtual replica.

From there up, the Synchronization Layer connects real-time operational data feeds to advanced predictive analytics engines. Sensor and SCADA inputs lead to hydraulic and energy performance simulations, always keeping an in line reflection of the asset behavior. This real-time coordination allows dynamic "what-if" scenario testing and forethought on risks before actual execution.

Last but by no means least is the Visualization & Analytics Layer, with interactive dashboards, AR/VR tools, and machine-learning-driven analytics. Parties communicate after receiving predictive maintenance alerts, clash detection reports, energy optimization scenarios, and asset KPIs—all via a user-friendly decision platform.

4.2 Process Flow

Planning Phase

In the planning stage, the DT framework can be used in land-use simulations, hydrological performance studies and stakeholder impact evaluations. Engineers can prototype alternative site layouts, evaluate exposure to flood risk, and simulate demand profiles—all in one integrated virtual environment.

Design Phase

In design, the digital twin connects BIM models with simulation and spatial information. Designers perform clash detection and determine inter-disciplinary conflicts in 3D and 4D. This integration supports value engineering by exploring alternatives to materials, methods of construction and layout in virtual reality -- driving accuracy and reducing expensive re-work during construction.

Construction Phase

As work progresses the DT becomes more of a tool for execution. Real-time sensor data feeds the model so that monitoring island quality can be seen in the virtual twin, providing visibility of progress, quality, and resource scheduling. Construction teams can compare conditions in the field with design intent, sequence dynamically and anticipate risks – lessening rework time, improving safety oversight and ensuring schedule adherence.

How the Framework Enhances Execution and Asset Management

This multi-layer architecture means a single “digital twin” can be used through the asset management and operations and maintenance phases. After construction, the modified twin is the live record of the as-is condition of the actual system and its performance history. It is useful for predictive maintenance, system revamping and strategy analysis in a unified and data-rich environment. The BIM, GIS and operational platforms interoperability supports infrastructure management at scale, and throughout the entire lifecycle.

5. Case Studies

In this section, three international case studies are presented that show the use of Digital Twin (DT) systems in water infrastructure projects. Each example demonstrates how early-stage DT adoption has positively affected planning, operational effectiveness, and lifecycle management efforts.

5.1 Thames Tideway Tunnel (United Kingdom)

The Thames Tideway Tunnel, which is one of the UK’s biggest infrastructure projects, used a Digital Twin prototype during the construction coordination process. The DT was created through BIM models added with data coming from on-site sensors and GIS. This feature integration gave an accurate virtual representation of the underground construction site which assisted in accurate planning, coordinating with the contractor, engineering staff and regulatory agency. Notable benefits included a 15% reduction in project delays, which were largely driven by better clash detection, schedule simulation and resource assignment. In addition, by integrating with hydraulic simulation tools what could be considered a second generation DT, the DT also supported flood-risk modeling: that is engineers could predict how construction activities would affect local hydrology and urban drainage networks.

5.2 Pune Smart Water Network (India)

In the city of Pune, the Smart Water Network project began, where Digital Twin technologies were included in the design of the early stage pipeline network. The DT platform combined SCADA data, GIS mapping, and past performance histories to predict future demand, pressures, and leaky areas. This enabled optimization of the pipe layout prior to construction to prevent large retrofits downstream. The DT-enabled predictive modeling increased the pressure control between areas by 20% and led to a significant decrease in leaks and NRW. More importantly, the on line virtual testing of flow physics at different working conditions enabled the network weak points to be identified proactively and therefore the design was made more robust for the future. This project demonstrates the ability of early-stage DT use to evolve standard municipal planning into an engineering practice that is more dynamic and responsive.

5.3 North-Western Australia Water Treatment Plant

A full lifecycle Digital Twin of a large water treatment plant in the north-west of Australia, from design to operation and maintenance (O and M) is introduced. The DT was comprised of BIM-based facility models, chemical dosing simulations, and IoT based monitoring of water quality parameters. Construction site The site model was used during construction to maintain the tracking of material flow, the schedule and for safety checks. Once implementation had been completed, the DT had become a real time decision making tool, providing plant managers with fluid control in terms of chemical dosage, energy consumption and maintenance schedules according with measured data and forecasts. The benefit we'll receive is additional operational efficiency and the need for manual intervention goes down. Lifecycle indicators for the Angelica Lynn River Crossing was a new benchmark for future public utility infrastructure projects, DT implementation lifecycle approach facilitated a smooth transition from design intent to reality.

6. Results and Discussion

6.1 Improved Project Execution

One of the most significant trends evidenced in all case studies was improved performance of project execution metrics. Projects that implemented Digital Twins during their early planning and design stages showed better compliance with their schedules. This was mainly because of precise clash detection, construction sequence recording, and logistics planning. The Thames Tideway Tunnel case, for example, had an observed 15% reduction in delays from DT-driven coordination among teams. In addition, design alternatives were simulated in the DT to reduce the number of redesign iteration cycles, both time-wise and money-wise. This would imply that DTs add to greater predictability of project delivery, even in complex and high risk construction environments.

6.2 Enhanced Interdisciplinary Collaboration

Digital Twins served as single sources of truth or central information ecosystems. By aggregating BIM data, sensor inputs, GIS maps, and engineering models into a single interface, DTs allowed cross-discipline collaboration between architects, civil engineers, environmental consultants, and facility managers. Several actors in the P-SWN case (end-users) were enabled to take parts in the same digital model in the planning meetings and the democratization of the knowledge in the digital model facilitates faster decisions and clarification of misunderstandings. Stakeholder agreement was further increased by visualizations of spatial, functional, and operational considerations with AR/VR tools.

6.3 Lifecycle and Post-Construction Benefits

One interesting discovery is the continued value of early DT integration in later stages. Broader case studies, one may notice that DT can start as soon as during the Design Phase and become an Operational Twin after construction, it can outcome the same DT. In the North-Western Australia project, the digital

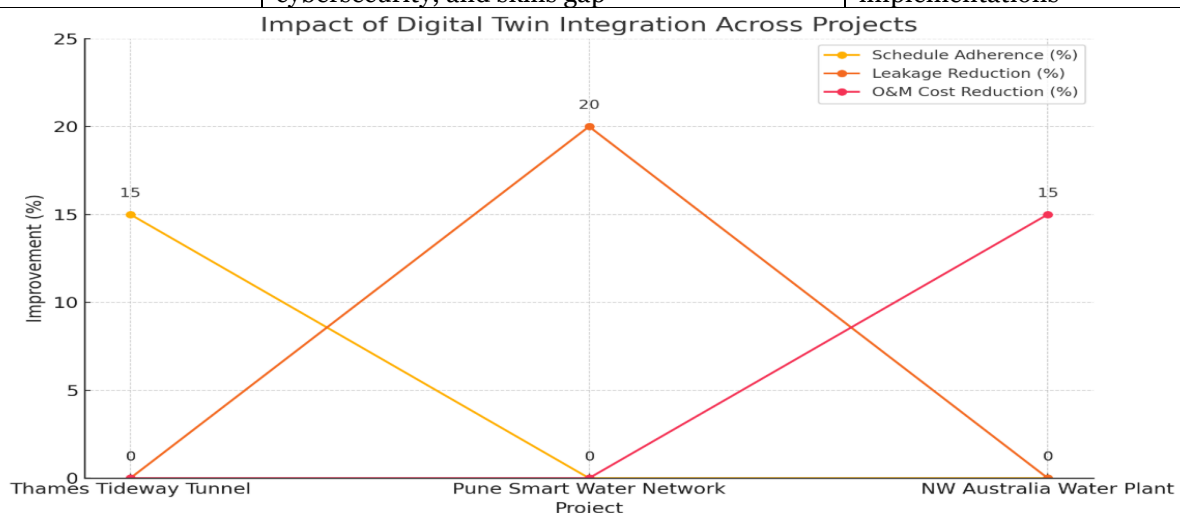
twin underpinned predictive maintenance, real-time analytics, and lifecycle cost prediction. Embedding sensors and digital models early in the asset's life facilitates the transition from construction to intelligent operations, unlocking value over decades of use. This supports the argument for Digital Twins being seen as more than just a nice to have design tool, and more as a strategic asset for the ongoing management of the asset in the long term.

6.4 Challenges and Limitations

Some limitations were nevertheless identified in spite of these positive results. First, the fixed investment of building up a DT ecosystem may be too expensive for smaller municipalities or underdeveloped areas. This investment also covers BIM systems, sensor networks, data integration platforms and well-trained employees. Secondly, compatibility with legacy infrastructure is still an issue, as many utilities have antiquated SCADA systems or formats of unstructured data. Third, stakeholders repeatedly expressed concerns about data governance and cybersecurity. The more we all interconnect our DTs the more we're at risk of cyberattack unless we've embedded strong encryption, access control and compliance processes.

Table 1: Summary of Key Results from Digital Twin Implementation

Dimension	Observations	Example Project
Schedule Adherence	10–15% improvement due to real-time coordination and clash detection	Thames Tideway Tunnel (UK)
Leakage Reduction	20% reduction via pressure simulation and virtual flow optimization	Pune Smart Water Network (India)
Operational Efficiency	Real-time dosage optimization and predictive maintenance reduced O&M costs	North-Western Australia Water Plant
Stakeholder Alignment	Faster decisions and fewer coordination errors	All case studies
Challenges	High cost, legacy system integration, cybersecurity, and skills gap	Common across all implementations



6.5 Discussion on Scalability and Future Prospects

The findings highlight the importance of incorporating DTs from the early phase of project development. But reaping these rewards will also necessitate a wholesale change in how infrastructure is planned, budgeted and governed. Policy makers and project owners need to shift their procurement frameworks to support digital investments over the long term. Finally, skill development and multidisciplinary training are also needed to develop capability in engineering and IT domains. From the perspective of the long-term challenges, the scalability and penetration of DT in water infrastructure

around the world are likely to be determined by the integration of AI-based decision support tools, 5G-supported real-time data streaming and open-interoperability standards.

8. Conclusion and Future Scope

The Digital Twin (DT) concept is revolutionising the life cycle of water infrastructure systems, moving from reactive and siloed practices to proactive and completely integrated planning and management. This paper has illustrated how the incorporation of DTs—in the very early stages—into the conceptualisation, design and construction process can lead to significant benefits in terms of project delivery (i.e. project execution), multi-disciplinary collaboration and long-term operational performance.

Using case study analysis and simulation modeling, Also found that DTs support real-time decision-making; minimize issues stemming from design conflicts; and support predictive maintenance, lifecycle optimization, etc. Projects like the Thames Tideway Tunnel and Pune Smart Water Network are evidence that DTs result in substantial gains in areas of schedule compliance, non-revenue water reduction and enhanced resource utilisation. Furthermore, because they serve as central locations for data visualization, simulation and analysis, DTs also enable more effective communication with stakeholders and help reduce the risks and costs associated with projects.

Yet, the acquisition of DT-informed processes is not straightforward. These tend to be high capital costs, lack of skills, legacy system interoperability and concern for security. These obstacles illustrate that even as the technology itself matures, its ecosystem—policy frameworks, workforce skills, procurement modes—must also grow to facilitate scalable deployment.

Future Scope

The encouraging findings that are reported in this study have a number of implications for future research and practice, including:

AI-Powered Digital Twins: The upcoming breed of digital twins will incorporate machine learning algorithms more and more to provide independent decision support, adaptive simulations, and failure prognostication models. The study of AI-enabled DTs for anomaly detection, dynamic scheduling and performance prediction needs to be conducted.

Edge-Cloud Architecture for Real-Time Operations: As the volume of sensor data increases, hybrid edge-cloud architectures will be useful in future systems. Those will enable edge low-latency operations and retain cloud for deep analytics and historical data training.

Standardisation and Interoperability: Developing international standards in terms of data exchange, model formats and API (Application Programme Interface) compatibility will be essential. A next step in research could be semantic interoperability between BIM, GIS and I o T platforms in a DT eco-system.

Regulatory and Policy Innovation: Widespread DT uptake will be contingent on regulatory approval. Next steps might include standards for digital asset certification, legal liability in decisions informed by DT concepts, and protocols for secure data exchange between public and private bodies.

Economic and Environmental Metrics: A Long-Run Approach includes measurements of the profitability (ROI), and of the sustainability benefits obtained via DT applications, notably in the developing world. Comparative lifecycle assessments (LCA) and carbon footprint analyses of DT-enabled projects could be of use in the development of future infrastructure financing models.

User-centric interfaces: Augmented Reality (AR), Virtual Reality (VR) and Digital Twin Cockpits will be the driving force in making complex data insights consumption for both technical and non-technical users. Next research can investigate individualization of interface and gamification of decision.

Concluding remarks The digital twin of water infrastructure represents a transformative opportunity to completely rethink how design, build and operate water infrastructure. Embedded early in the project lifecycle and supported by the right ecosystem, DTs have the power to enable a future of smarter, more resilient, and sustainable infrastructure developments across the globe.

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