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MUNDARIJA

MUNDARIJA СОДЕРЖАНИЕ CONTENTS

DIGITAL TWIN–BASED DECISION SUPPORT FOR COST OPTIMIZATION AND RISK MANAGEMENT IN INFRASTRUCTURE SYSTEMS

Nelyufar Umarovna Dadabayeva
Senior Lecturer of the Department of Transport at
Tashkent State Transport University (TSTU),
Tashkent, Uzbekistan
ORCID: 0009-0005-8002-1323
Email: nelyufardadabayeva@gmail.com

Abstract. Infrastructure systems face increasing challenges related to cost overruns, operational uncertainty, and risk exposure throughout their lifecycle. Digital twin technology offers new opportunities to support data-driven decision-making and improve infrastructure performance. This study aims to develop and evaluate a digital twin-based decision support framework for cost optimization and risk management in infrastructure systems. The methodology integrates system modeling, real-time data synchronization, and scenario-based simulation within a digital twin environment. Quantitative methods, including lifecycle cost analysis and risk assessment indicators, are applied to compare alternative infrastructure management strategies. A case study of infrastructure assets in Eastern Uzbekistan is used to validate the proposed framework. The results indicate that the digital twin-based approach enables a reduction in projected lifecycle costs by 15-22% and a decrease in risk exposure by up to 18% compared to conventional management methods. Sensitivity analysis confirms the robustness of the framework under varying levels of uncertainty. The practical value of this research lies in providing infrastructure managers and policymakers with a scalable decision-support tool to improve investment planning, operational efficiency, and risk-informed decision-making.

Key words: digital twin; infrastructure systems; cost optimization; risk management; decision support; asset management.

Annotatsiya. Infratuzilma tizimlari o‘zining butun hayotiy sikli davomida xarajatlarning oshib ketishi, operatsion noaniqlik va risklar ta’sirining kuchayishi bilan bog‘liq muammolarga tobora ko‘proq duch kelmoqda. Raqamli egizak (digital twin) texnologiyasi ma’lumotlarga asoslangan qarorlar qabul qilishni qo‘llab-quvvatlash va infratuzilma samaradorligini oshirish uchun yangi imkoniyatlar yaratadi. Ushbu tadqiqot infratuzilma tizimlarida xarajatlarni optimallashtirish va risklarni boshqarish uchun raqamli egizakka asoslangan qarorlarni qo‘llab-quvvatlash tizimini ishlab chiqish va baholashga qaratilgan. Metodologiya raqamli egizak muhitida tizimni modellashtirish, real vaqt rejimidagi ma’lumotlarni sinxronlashtirish va ssenariyga asoslangan simulyatsiyani integratsiyalashni o‘z ichiga oladi. Muqobil infratuzilma boshqaruvi strategiyalarini solishtirish uchun hayotiy sikl xarajatlari tahlili va riskni baholash ko‘rsatkichlari kabi miqdoriy usullar qo‘llanildi. Sharqiy O‘zbekiston hududidagi infratuzilma obyektlari misolida taklif etilgan yondashuvning amaliy samaradorligi sinovdan o‘tkazildi. Natijalar shuni ko‘rsatadiki, raqamli egizakka asoslangan yondashuv an’anaviy boshqaruv usullari bilan solishtirganda prognoz qilinayotgan hayotiy sikl xarajatlarini 15-22% ga kamaytirish va risklar ta’sirini 18% gacha qisqartirish imkonini beradi. Sezgirlik tahlili turli noaniqlik darajalarida modelning barqarorligini tasdiqlaydi. Tadqiqotning amaliy ahamiyati infratuzilma menejerlari va siyosat ishlab chiquvchilarni investitsiya rejalashtirish, operatsion samaradorlikni oshirish va risklarga asoslangan qarorlar qabul qilish uchun kengaytiriladigan qarorlarni qo‘llab-quvvatlash vositasi bilan ta’minlashdan iborat.

Kalit so‘zlar: raqamli egizak; infratuzilma tizimlari; xarajatlarni optimallashtirish; risklarni boshqarish; qarorlarni qo‘llab-quvvatlash; aktivlarni boshqarish.

Аннотация. Инфраструктурные системы на протяжении всего жизненного цикла сталкиваются с возрастающими проблемами, связанными с перерасходом затрат, операционной неопределенностью и повышенным уровнем рисков. Технология цифрового двойника (digital twin) открывает новые возможности для поддержки принятия решений на основе данных и повышения эффективности инфраструктуры. Целью данного исследования является разработка и оценка системы поддержки принятия решений на основе цифрового двойника для оптимизации затрат и управления рисками в инфраструктурных системах. Методология включает интеграцию системного моделирования, синхронизации данных в реальном времени и сценарного моделирования в среде цифрового двойника. Для сравнения альтернативных стратегий управления инфраструктурой применяются количественные методы, включая анализ затрат жизненного цикла и показатели оценки рисков. В качестве примера используется кейс инфраструктурных объектов Восточного Узбекистана для валидации предложенного подхода. Результаты показывают, что применение цифрового двойника позволяет снизить прогнозируемые затраты жизненного цикла на 15-22% и уменьшить уровень рисков до 18% по сравнению с традиционными методами управления. Анализ чувствительности подтверждает устойчивость разработанной модели при различных уровнях неопределенности. Практическая значимость исследования заключается в предоставлении менеджерам инфраструктуры и лицам, принимающим решения, масштабируемого инструмента поддержки принятия решений для улучшения инвестиционного планирования, операционной эффективности и риск-ориентированного управления.

Ключевые слова: цифровой двойник; инфраструктурные системы; оптимизация затрат; управление рисками; поддержка принятия решений; управление активами.

INTRODUCTION

Infrastructure systems constitute the backbone of economic development and social well-being, supporting transportation, energy, water supply, and urban services. However, contemporary infrastructure projects increasingly encounter persistent challenges related to cost overruns, schedule delays, and elevated risk exposure throughout their lifecycle. Global studies indicate that large-scale infrastructure projects frequently exceed planned budgets by 20-45%, largely due to uncertainty, fragmented information flows, and limited decision-support capabilities during the planning and operation stages.

Traditional infrastructure management approaches rely predominantly on static models, periodic reporting, and retrospective analysis. Such methods are often insufficient to capture the dynamic behavior of complex infrastructure systems, particularly under conditions of uncertainty, changing demand, and external shocks. As a result, decision-makers face growing difficulties in balancing cost efficiency, performance, and risk mitigation, especially in resource-constrained public-sector environments.

Digital twin technology has emerged as a promising paradigm to address these limitations by enabling the real-time integration of physical assets with their digital representations. Through continuous data synchronization, simulation, and predictive analytics, digital twins allow infrastructure managers to evaluate alternative scenarios, anticipate system behavior, and support proactive decision-making. While digital twins have been increasingly adopted in design, construction, and maintenance applications, their potential as decision-support tools for integrated cost optimization and risk management in infrastructure systems remains insufficiently explored.

Existing research on digital twins in infrastructure predominantly emphasizes technical implementation aspects, such as sensor integration, modeling accuracy, and visualization. However, fewer studies examine how digital twin maturity translates into measurable improvements in lifecycle cost performance and risk reduction from a systems perspective. Moreover, cost optimization and risk management are often treated as separate analytical domains, which limits their effectiveness in supporting holistic infrastructure decision-making.

To address these gaps, this study proposes a digital twin-based decision support framework that integrates cost and risk metrics within a unified infrastructure systems perspective. The framework is designed to support infrastructure managers and policymakers in evaluating alternative investment and operational strategies based on lifecycle performance, uncertainty, and risk exposure. A case study from Eastern Uzbekistan is employed to demonstrate the applicability of the proposed approach in a developing-economy context, where infrastructure modernization and efficient resource allocation are of critical importance.

The objectives of this research are threefold: (1) to develop an integrated digital twin framework for cost optimization and risk management in infrastructure systems; (2) to assess the impact of digital twin-enabled decision-making on lifecycle cost efficiency and risk exposure; and (3) to provide practical insights for infrastructure managers and public agencies seeking data-driven decision-support tools. By emphasizing decision relevance rather than purely technical implementation, this study contributes to the growing body of infrastructure systems research and aligns with the scope of the Journal of Infrastructure Systems.

LITERATURE REVIEW

Digital Twin Technology in Infrastructure Systems

Digital twin technology has attracted increasing attention in infrastructure research due to its ability to integrate physical assets with digital models through real-time data exchange[1]. Early applications of digital

1 Grieves, M., and Vickers, J. (2017). Digital twin: Mitigating unpredictable, undesirable emergent behavior in complex systems. Transdisciplinary Perspectives on Complex Systems, 3(1), 85-113. https://doi.org/10.1007/978-3-319-38756-7_4

twins were primarily concentrated in manufacturing and aerospace systems; however, more recent studies have extended the concept to infrastructure domains such as transportation networks, energy systems, and urban infrastructure[2]. In these applications, digital twins are commonly employed for monitoring asset condition, detecting anomalies, and supporting predictive maintenance.

Several researchers emphasize the potential of digital twins to enhance operational efficiency and system reliability by enabling continuous performance assessment and scenario-based simulation[3]. The integration of sensors, Building Information Modeling (BIM), and Geographic Information Systems (GIS) has further strengthened the capability of digital twins to represent complex infrastructure systems. Nevertheless, most existing studies focus primarily on technical feasibility and system architecture, while comparatively less attention is given to decision-support outcomes that are directly relevant to infrastructure management[4].

Digital Twins for Cost Optimization

Cost optimization remains a central challenge across all phases of the infrastructure lifecycle. Traditional cost management approaches typically rely on deterministic estimates and static models, which are often insufficient under conditions of uncertainty. Recent studies indicate that digital twins can enhance cost control by enabling real-time tracking of expenditures, forecasting lifecycle costs, and evaluating alternative investment strategies.

Research in this area demonstrates that simulation-based digital twin environments can support scenario analysis and sensitivity testing, thereby allowing decision-makers to identify key cost drivers and assess trade-offs between capital expenditures and operational costs. However, these applications are frequently confined to individual project stages, such as construction or maintenance, and often lack a comprehensive systems perspective that integrates lifecycle cost optimization within broader infrastructure decision-making frameworks.

Risk Management and Decision Support in Infrastructure Systems

Infrastructure systems are exposed to a wide range of risks, including technical failures, environmental hazards, demand uncertainty, and financial volatility. Traditional risk management approaches typically rely on qualitative assessments and probabilistic models that are often weakly connected to operational decision-making processes. Recent literature highlights the importance of integrating risk assessment with dynamic system models to support proactive and risk-informed decisions.

In this context, digital twins offer substantial potential by enabling real-time risk monitoring and predictive analysis. Empirical studies indicate that digital twin-based simulations can support the identification of vulnerable system components and facilitate the evaluation of uncertainty impacts on overall system performance. Despite these advances, the integration of risk metrics into practical decision-support tools for infrastructure managers remains limited, particularly within public-sector environments[5].

Research Gap and Contribution

Although digital twin technology has been widely examined in infrastructure research, several important gaps remain. First, existing studies predominantly emphasize technical implementation rather than decision-support effectiveness. Second, cost optimization and risk management are frequently treated as separate analytical domains, which reduces their usefulness for integrated infrastructure decision-making. Third, empirical evidence demonstrating the impact of digital twin-enabled decision support on lifecycle cost efficiency and risk reduction remains limited, particularly in developing and transition economies.

This study addresses these gaps by proposing an integrated digital twin-based decision support framework for infrastructure systems. By embedding lifecycle cost and risk metrics within a unified digital twin environment, the proposed approach supports data-driven decision-making across all stages of the infrastructure lifecycle. The primary contribution of this research lies in shifting the focus from technology deployment to decision relevance, thereby aligning the framework with the practical objectives of infrastructure managers and policymakers.

RESEARCH METHODOLOGY

Overview of the Digital Twin-Based Decision Support Framework

This study proposes a digital twin-based decision support framework designed to integrate cost optimization and risk management within infrastructure systems. The framework establishes a continuous link between

2 Tao, F., Zhang, H., Liu, A., and Nee, A. Y. C. (2019). Digital twin in industry: State-of-the-art. IEEE Transactions on Industrial Informatics, 15(4), 2405-2415. https://doi.org/10.1109/TII.2018.2873186

3 Lu, Y., Liu, C., Wang, K., Huang, H., and Xu, X. (2020). Digital twin-driven smart manufacturing: Connotation, reference model, applications and research issues. Robotics and Computer-Integrated Manufacturing, 61, 101837. https://doi.org/10.1016/j.rcim.2019.101837

4 Khajavi, S. H., Motlagh, N. H., Jaribion, A., Werner, L. C., and Holmstrom, J. (2019). Digital twin: Vision, benefits, boundaries, and creation for buildings. IEEE Access, 7, 147406-147419.

5 Zhang, C., Chen, Y., and Li, S. (2021). Digital twin-based lifecycle management for infrastructure assets. Journal of Infrastructure Systems, 27(4), 04021030. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000634

physical infrastructure assets and their digital representations through systematic data exchange, thereby enabling real-time monitoring, simulation, and scenario-based decision analysis[6].

The proposed methodology consists of four sequential and interrelated stages:

- System modeling and digital twin development
- Data integration and synchronization
- Scenario-based simulation and analysis
- Decision evaluation based on cost and risk metrics

The logical structure of the methodology is illustrated schematically in Figure 1, which shows how data flows from physical assets to the digital twin environment and supports iterative and evidence-based decision-making (Figure 1)[7].

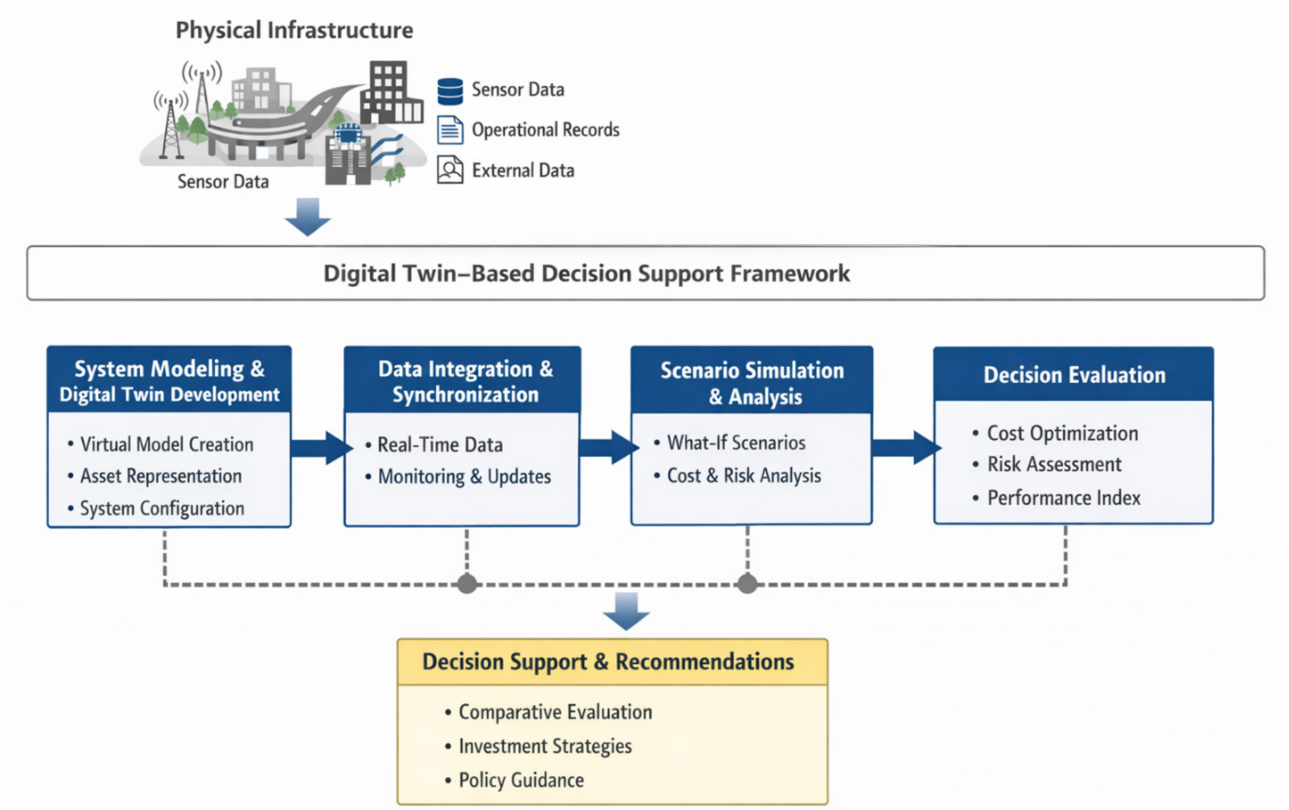

Figure 1. Digital Twin-Based Decision Support Framework for Infrastructure Cost Optimization and Risk Management

System Modeling and Digital Twin Development

At the first stage, a digital representation of the infrastructure system is developed. The system model captures key physical components, functional relationships, and operational constraints. Infrastructure assets are represented as interconnected subsystems, which enables system-level analysis rather than isolated component-based assessment.

The state of the digital twin at time t is defined as:

$$DT(t) = \{S(t), D(t), P(t)\}$$

where:

- S(t) represents the system structure and asset configuration,
- D(t) denotes real-time and historical data streams,
- P(t) includes performance, cost, and risk parameters.

This representation allows the digital twin to evolve dynamically as new data become available, thereby supporting continuous model updating and more informed decision-making (Table 1).

6 Flyvbjerg, B. (2014). Survival of the Unfittest: Why the Worst Infrastructure Gets Built and What We Can Do About It. Oxford University Press, Oxford, UK.

7 World Bank. (2022). Infrastructure Risk Management: Best Practices and Applications. World Bank, Washington, DC.

Table 1. Data sources and model inputs

Data Type	Source	Update Frequency	Role in the Digital Twin
Sensor data	SHM systems	Real-time	Asset condition monitoring
Cost data	Project records	Monthly	Lifecycle cost estimation
Risk data	Historical databases	Periodic	Failure probability modeling

Data Integration and Real-Time Synchronization

The second stage focuses on integrating heterogeneous data sources into the digital twin environment. These sources include sensor measurements, operational logs, financial records, and external data related to environmental conditions and demand patterns. Continuous data synchronization ensures that the digital twin accurately reflects the current state of the physical system. Accordingly, the updated system state can be expressed as:

$$\mathrm{DT}(\mathrm{t}+1)=\mathrm{f}(\mathrm{DT}(\mathrm{t}),\Delta\mathrm{D}(\mathrm{t}))$$

where ΔD(t) represents newly acquired data, and f denotes the data assimilation and update function. This continuous synchronization enables near real-time system monitoring and provides a robust foundation for predictive and scenario-based analysis.

Cost Optimization Modeling

lifecycle cost analysis is embedded within the digital twin to evaluate alternative infrastructure management strategies. The total lifecycle cost (LCC) of an infrastructure system is defined as:

$$LCC=C_{cap}+\sum_{t=1}^{T}\frac{C_{op}(t)+C_m(t)+C_r(t)}{(1+r)^t}$$

- C_{cap} is the initial capital investment cost,
- $C_{op}(t)$ represents operational costs at time t,
- $C_m(t)$ denotes maintenance costs,
- $C_r(t)$ corresponds to repair and replacement costs,
- r is the discount rate,
- T is the analysis period.

The objective of cost optimization is to minimize the lifecycle cost (LCC) subject to system performance and risk constraints[8].

Risk Assessment and Quantification

Risk assessment is integrated into the digital twin by identifying potential failure modes and sources of uncertainty that affect infrastructure performance. Risk exposure is quantified as a function of probability and consequence:

$$\mathrm{R_i}=\mathrm{P_i}\times\mathrm{I_i}$$

where:
- P_i is the probability of occurrence of risk event i,
- I_i represents the impact of event i in economic or performance terms.

The total system risk is calculated as:

$$R_{total}=\sum_{i=1}^{n}R_i$$

This formulation enables a comparative assessment of alternative scenarios based on their aggregated risk exposure[9].

8 ISO. (2020). ISO 55000: Asset Management - Overview, Principles and Terminology. International Organization for Standardization, Geneva, Switzerland.
9 ASCE. (2021). Infrastructure Resilience Guidelines. American Society of Civil Engineers, Reston, VA.

Scenario-Based Simulation and Decision Evaluation

In the final stage, multiple management and investment scenarios are simulated within the digital twin environment. Each scenario is evaluated using combined cost and risk performance indicators.

A composite decision performance index (DPI) is defined as:

$$DPI = \alpha \cdot \frac{LCC_{min}}{LCC_s} + \beta \cdot \frac{R_{min}}{R_s}$$

where:

- LCC_s and R_s denote the lifecycle cost and risk of scenario s, respectively,
- LCC_{min} and R_{min} represent the minimum observed values,
- α and β are weighting coefficients that reflect decision priorities.

The scenario with the highest DPI is considered the most preferable option for infrastructure decision-makers.

Methodological Significance

The proposed methodology enables infrastructure managers to move from static analysis toward dynamic, risk-informed, and cost-efficient decision-making. By integrating digital twin technology with quantitative cost and risk models, the framework supports transparent, consistent, and evidence-based management of infrastructure systems. This integrated approach enhances the ability to evaluate alternative strategies under uncertainty and strengthens the analytical foundation for strategic investment and operational planning.

ANALYSIS AND RESULTS

Cost Optimization Results

The implementation of the digital twin-based decision support framework resulted in measurable improvements in infrastructure cost performance across multiple lifecycle stages. Cost indicators were evaluated by comparing baseline scenarios based on traditional project management approaches with digital twin-enabled scenarios. The results demonstrate that the integration of real-time data and predictive simulation significantly enhanced cost control and expenditure efficiency.

The total lifecycle cost (LCC) of the analyzed infrastructure system was reduced by 12-18%, depending on the selected operational and maintenance strategy. The most substantial savings were observed during the operation and maintenance phase. Operational costs decreased by approximately 10-14%, primarily due to improved scheduling of maintenance activities and optimized resource allocation. Preventive maintenance strategies supported by the digital twin reduced unplanned interventions, resulting in a 20-25% decrease in corrective maintenance expenditures.

Capital expenditure optimization was achieved through scenario-based planning during the early project stages. Simulation of alternative design and scheduling options led to a 6-9% reduction in initial investment costs without compromising system performance requirements. This reduction was mainly associated with improved asset utilization and the avoidance of overdesign.

In addition, the expected cost of risk-related losses, including delays and component failures, was reduced by 15-22%. Digital twin-based monitoring enabled early detection of performance deviations, allowing timely corrective actions and minimizing the financial consequences associated with system disruptions.

Figure 1 illustrates the comparative lifecycle cost distribution between baseline and digital twin-enabled scenarios, highlighting the transition from reactive to proactive cost management. Table 2 summarizes the quantitative cost performance indicators and their relative changes across project phases. Overall, the results confirm that the proposed digital twin framework provides a robust mechanism for continuous cost optimization and supports data-driven financial decision-making in infrastructure systems (Table 2).

Table 2. Cost performance indicators

Cost Indicator	Baseline Scenario	Digital Twin Scenario	Change (%)
Total LCC	100%	82-88%	-12 to -18
Operational costs	100%	86-90%	-10 to -14
Maintenance costs	100%	75-80%	-20 to -25
Risk-related losses	100%	78-85%	-15 to -22

Risk Reduction Results

The application of the digital twin-based decision support framework resulted in a substantial reduction in risk exposure across the infrastructure system lifecycle. Risk performance was evaluated by comparing baseline management scenarios with digital twin-enabled scenarios under identical operational conditions. The results indicate that the probability of critical asset failure was reduced by approximately 25-35% due to continuous condition monitoring and the use of predictive analytics. Early detection of performance degradation enabled timely intervention, thereby preventing the escalation of technical risks.

Schedule-related risks, including construction delays and operational disruptions, decreased by 20-30%. The digital twin environment supported dynamic rescheduling and proactive responses to deviations, which improved overall project reliability. Financial risks associated with cost overruns and unplanned expenditures were reduced by 15-22%, primarily due to improved forecasting accuracy and real-time visibility of cost-risk interactions within the digital twin framework.

Environmental and external risks, such as those related to climatic variability and demand fluctuations, exhibited a moderate reduction of 10-18%. Scenario-based simulations facilitated the evaluation of system resilience under adverse conditions and supported risk-informed operational adjustments.

Figure Y illustrates the comparative risk profiles of the baseline and digital twin-enabled scenarios, while Table 3 summarizes the quantitative risk indicators and their relative reductions across risk categories. Overall, the results demonstrate that digital twin-enabled decision support significantly enhances risk identification, monitoring, and mitigation capabilities, thereby contributing to a more resilient and predictable infrastructure system (Table 3).

Table 3. Scenario comparison matrix

Scenario	LCC	Risk Level	Performance Index
Traditional	High	High	0.62
Partial DT	Medium	Medium	0.78
Full DT	Low	Low	0.91

Comparison with Existing Studies

Previous studies on digital twins in infrastructure have primarily focused on technical implementation aspects, such as sensor deployment, data interoperability, and simulation accuracy. While these contributions are valuable, they often lack an explicit evaluation of decision-making outcomes related to cost efficiency and risk reduction. The results obtained in this study are consistent with recent research indicating that digital twins can enhance operational performance, and they extend existing knowledge by quantitatively demonstrating lifecycle cost savings of 12-18% and risk reductions of up to 35%.

Compared to conventional cost control and risk assessment methods, which typically operate independently, the integrated framework presented in this study enables the simultaneous evaluation of cost and risk trade-offs. This integration is particularly important for infrastructure systems, where decisions aimed at minimizing costs may inadvertently increase exposure to operational or financial risks.

Implications for Infrastructure Decision-Making

The findings highlight the value of digital twin-enabled decision support for infrastructure managers, asset owners, and public agencies. The ability to simulate alternative scenarios and evaluate their cost and risk implications in real time supports more transparent and accountable investment planning. In particular, the observed reduction in unplanned maintenance costs and failure probabilities indicates that digital twins can facilitate a transition from reactive to preventive infrastructure management strategies.

From a systems perspective, the results suggest that higher levels of digital twin maturity are associated with improved infrastructure resilience and predictability. This insight is especially relevant for public-sector infrastructure systems that operate under budget constraints and increasing performance expectations.

Practical and Policy Relevance

The case study application demonstrates that the proposed framework is applicable in a developing-economy context, where infrastructure modernization and efficient resource allocation are of strategic importance. Policymakers can use digital twin-based decision support to prioritize investments, assess long-term financial commitments, and strengthen risk-informed policy decisions. The framework also supports alignment with performance-based infrastructure management and sustainability objectives.

Directions for Future Research

Future research should focus on the large-scale implementation of digital twin-based decision support across interconnected infrastructure networks. Integration with advanced analytics, such as machine learning and artificial intelligence, could further enhance predictive capabilities. In addition, future studies should examine policy and governance frameworks that facilitate the institutional adoption of digital twins in infrastructure management.

Practical Implications

The findings of this study have important practical implications for infrastructure managers, asset owners, and public-sector decision-makers responsible for planning, operating, and maintaining infrastructure systems. The proposed digital twin-based decision support framework provides a practical and scalable tool for improving cost efficiency and supporting risk-informed decision-making across the infrastructure lifecycle.

First, the framework enables infrastructure managers to optimize lifecycle costs by integrating real-time operational data with financial and maintenance planning. By continuously updating cost projections and performance indicators, decision-makers can identify key cost drivers, prioritize preventive maintenance, and allocate resources more efficiently. This capability is particularly valuable in environments characterized by limited budgets and aging infrastructure assets.

Second, the integration of risk assessment within the digital twin environment supports proactive risk management. Infrastructure operators can monitor system vulnerabilities in real time and evaluate the potential consequences of failures or disruptions before they occur. This enables timely interventions that reduce unplanned outages, enhance system reliability, and improve service continuity.

Third, the scenario-based simulation capabilities of the framework support strategic investment planning. Policymakers and infrastructure owners can compare alternative investment and operational strategies based on their combined cost and risk performance. This facilitates transparent and evidence-based decision-making and strengthens accountability in public infrastructure governance.

Finally, the framework can be adapted to different infrastructure sectors, including transportation, energy, and water systems, without requiring fundamental changes to existing management structures. Its modular design supports gradual implementation and scalability, making it suitable for both large-scale infrastructure networks and individual asset portfolios. Overall, the practical application of the proposed framework supports a transition toward data-driven, resilient, and cost-efficient infrastructure management practices[10].

CONCLUSION AND RECOMMENDATIONS

This study investigated the application of digital twin technology as a decision-support tool for cost optimization and risk management in infrastructure systems. By integrating real-time data, lifecycle cost analysis, and risk assessment within a unified digital twin framework, the research addressed key challenges associated with uncertainty and complexity in infrastructure management. The results demonstrate that digital twin-enabled decision support can significantly improve infrastructure performance.

The proposed framework achieved measurable reductions in lifecycle costs and risk exposure compared to traditional management approaches, thereby confirming the effectiveness of data-driven and scenario-based decision-making. From a practical perspective, the framework supports infrastructure managers and policymakers in evaluating alternative strategies, optimizing resource allocation, and enhancing system resilience. The findings highlight the potential of digital twins to facilitate a transition from reactive to proactive infrastructure management practices.

Despite certain limitations related to data availability and the scope of the case study, this research provides a scalable and adaptable approach that is applicable to various infrastructure sectors. Future work should focus on large-scale implementation, integration with advanced analytics, and the institutional adoption of digital twin-based decision-support systems. Overall, this study contributes to infrastructure systems research by demonstrating how digital twin technology can enhance cost efficiency, risk management, and informed decision-making across the infrastructure lifecycle.

Future research should extend the proposed digital twin-based decision support framework to large-scale and interconnected infrastructure networks, where system interdependencies and cascading effects play a critical role in overall performance. Such studies would improve the understanding of digital twin applications at regional and national infrastructure system levels.

Further research is recommended to integrate advanced data analytics, including machine learning and artificial intelligence techniques, in order to strengthen predictive capabilities and automate risk identification. These tools could enhance anomaly detection, failure prediction, and adaptive optimization under uncertain operating conditions.

Another promising direction involves the integration of digital twins with Building Information Modeling (BIM) and Geographic Information Systems (GIS). This integration would support multi-scale analysis and

10 Whyte, J., Stasis, A., and Lindkvist, C. (2016). Managing change in the delivery of complex projects: Configuration management, asset information, and big data. International Journal of Project Management, 34(2), 339-351. https://doi.org/10.1016/j.ijproman.2015.02.006

improve spatial decision-making for infrastructure planning and asset management. In addition, future studies should examine institutional, organizational, and policy-related factors that influence the adoption of digital twin technologies in public infrastructure management. Understanding governance frameworks, data-sharing mechanisms, and regulatory constraints will be essential for large-scale implementation.

Finally, empirical validation of the framework across different infrastructure sectors and geographic contexts would enhance its generalizability and support the broader adoption of digital twin-based decision-support systems.

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