RESEARCH IN PROGRESS

CONSTRUCTING A COST–BENEFIT ANALYSIS FRAMEWORK FOR DIGITAL TWIN–ENABLED SPATIAL PLANNING: ARTICULATING (HIDDEN) COSTS AND (IMPLICIT) BENEFITS IN GOVERNMENTAL ORGANIZATIONS

DOI
https://doi.org/10.18690/um.fov.4.2026.66

ISBN
978-961-299-152-4

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Digital Twins (DTs) are increasingly used in urban planning and public-sector spatial development to support evidence-based decision-making and scenario analysis. However, many DT initiatives struggle to progress beyond pilot stages (Hiller et al., 2026), partly due to the absence of a clear and validated cost–benefit analysis (CBA) framework. Existing evaluations often underestimate lifecycle costs while failing to adequately articulate indirect and intangible benefits such as improved decision quality, stakeholder engagement, and transparency. This research-in-progress study tries to address this gap by asking how hidden costs and implicit benefits of DTs in public-area development can be identified and structured into a first version of a CBA framework. Using a Design Science approach, we combine a scoping review further supplemented with exploratory expert interviews in a Dutch spatial planning context. Preliminary findings highlight lifecycle and governance-related costs and indicate that DT value primarily emerges through improved decision quality and reduced downstream failure costs, though further detailing and validation is required in future research.

Keywords:
cost-benefit analysis,
spatial planning,
digital twin technology,
Bled eConference,
research in progress

University of Maribor Press

1 Introduction

Digital twins (DTs) are increasingly adopted in urban planning and public-sector spatial development as instruments for evidence-based decision-making, simulation, and scenario analysis (Asian Development Bank, 2025). By creating dynamic, data-driven virtual representations of physical environments, DTs promise to improve infrastructure planning processes, decrease conflicts during realization, optimize spatial intervention results, and support the evaluation of complex policy trade-offs. Governments and municipalities across Europe, including in the Netherlands, are experimenting with DT applications to address societal challenges such as climate adaptation, mobility transitions, energy infrastructure, and integrated area development (Calzati, 2023), see e.g., Figure 1. Despite these ambitions, many DT initiatives struggle to move beyond pilot or prototype stages. A recurring explanation in both academic and practitioner literature is the absence of a clear and validated cost–benefit analysis (CBA) framework to support long-term investment decisions. While DTs are often framed as transformative technologies, public organizations face substantial uncertainty regarding both their full cost structures and their realized benefits (Hiller et al., 2026).

Figure 1: 3D Utrecht DT Platform (Gemeente Utrecht, 2026)

The literature consistently points to two interrelated challenges. First, many DT-related costs remain "hidden" or underestimated. Beyond technical development, organizations must account for data governance arrangements, cybersecurity, legal compliance, training, change management, and long-term system evolution. Second, many of the anticipated benefits are implicit or difficult to quantify. These include improved interdepartmental collaboration, enhanced transparency in policy processes, increased stakeholder engagement, better risk awareness and risk prevention, less realization conflicts, better decision results and contributions to environmental resilience and social inclusion. These benefits also reflect underlying human and public values, such as fairness, transparency, inclusivity, and long-term societal well-being, that increasingly shape how digital infrastructures in the public domain are evaluated. Abbas et al. (2024), for instance, observe that most DT studies do not present quantifiable findings and call explicitly for comprehensive evaluation approaches, including formal cost–benefit analyses and clearer taxonomies of DT-specific cost and benefit categories. Without such structure, building a convincing business case remains difficult. In the Dutch context, similar patterns emerge. Municipalities and provinces are actively experimenting with DT solutions, yet these efforts often remain isolated and project-based. Studies of DT maturity in the Netherlands highlight the need for operationalized dimensions that extend beyond technical performance to include financial, operational, legal, policy, ethical, and societal considerations. Ecosystem analyses further describe a landscape characterized by strong technical innovation but limited integration of lifecycle value assessment in public-area development projects. As a result, DT initiatives frequently encounter difficulties in securing sustained political and financial support for scaling and institutionalization.

Taken together, these observations reveal a knowledge gap at the intersection of DT research and information systems evaluation. From an information systems perspective, DTs in governmental spatial planning should be assessed as socio-technical systems whose value depends not only on technical performance, but also on organizational embedding, user acceptance, governance arrangements, and broader decision-support and coordination benefits. Against this background, we address the following research question: How can both visible and hidden costs and both visible and often implicit benefits of DTs in public-area development be identified, articulated, and structured into a validated cost-benefit analysis framework? This Research-in-Progress paper adopts a design science perspective to lay the conceptual foundation for such a framework. By synthesizing existing research on DTs in urban and spatial planning and drawing on emerging Dutch practices, we aim to outline the core dimensions of a structured CBA framework that integrates both technical and organizational factors, as well as tangible and intangible value components.

2 Background and Related Work

Hidden and Lifecycle Costs: economic assessments show that DT investments extend far beyond initial model development. Thomas (2024) argues that DT viability must be evaluated across the full lifecycle, including data acquisition, validation, cybersecurity, governance, and long-term system use and maintenance. Similarly, Green et al. (2025), though from McKinsey, demonstrate that while DTs may improve infrastructure ROI, realising such gains requires sustained investments in interoperability, data pipelines, and organisational transformation. Urban DT reviews identify persistent integration and standardisation challenges, including data fragmentation and cross-domain coordination (Mazzetto, 2024; Syed Abdul Rahman et al., 2024). In practice, governance embedding generates additional costs: aligning DT outputs with policy cycles and monitoring frameworks requires new indicators, coordination mechanisms, and capacity building (De Lathouwer et al., 2024).

Implicit and Public-Value Benefits: While costs are often underestimated, benefits are frequently under-articulated. International frameworks highlight DT potential for multistakeholder coordination, risk anticipation, and resilience planning (World Economic Forum, 2022). However, such gains materialise indirectly through improved decision quality and reduced uncertainty rather than immediate financial returns. Huang and Tsou (2025) conceptualise DTs as socio-technical systems enabling cross-domain optimisation, potentially generating systemic sustainability benefits. In the Dutch context, Smit et al. (2023) identify quality dimensions such as legal robustness, ethical safeguards, and public-value orientation, indicating that DT value extends beyond efficiency to include trust and accountability. Case research confirms improved transparency and stakeholder understanding, yet difficulties in translating these into formal investment logic (Wolters, 2023). The literature demonstrates that DTs are applied across diverse domains, including industrial manufacturing, asset management (e.g., building information modeling), and healthcare (Hasan & Crawford, 2025; Tudor et al., 2025). However, the underlying assumptions about value differ across these streams. Some studies adopt an efficiency-oriented perspective and treat DT value primarily in terms of return on investment, time savings, or operational optimization, whereas other contributions emphasize lifecycle viability, governance complexity, and broader public-value effects such as transparency, accountability, and stakeholder inclusion. This creates a conceptual tension: what counts as a "benefit" in one framework may appear as a cost, constraint, or non-financial value dimension in another. In public spatial planning, this tension becomes particularly relevant because governmental DT applications are shaped not only by technical performance and financial considerations, but also by policy processes, interorganizational coordination, and societal legitimacy. The absence of a context-specific and validated CBA framework tailored to spatial planning by governmental organizations therefore motivates the present design science effort to systematically structure hidden costs and implicit benefits.

3 Research method & Preliminary Results

This research-in-progress study follows a design science approach (Hevner et al., 2004) to develop a CBA framework for DT-enabled spatial planning. We conducted a narrative review (Paré et al., 2015) to derive candidate cost and benefit categories. Within this review, we used Google Scholar as our search engine, utilizing "Cost AND Benefit AND Digital AND Twin" as our search query. Empirically, we currently conducted five exploratory semi-structured interviews with six experts (one interview had two experts present) from Dutch public and private organizations involved in DT initiatives in spatial planning. These experts were selected based on convinience sampling, but had multiple years of experience with building and implementing DTs in practice. We used direct coding in one round by one researcher focusing on identifying either candidate costs or benefits from both data sources. These were then reviewed by two reseachers, which led to the first iteration of the CBA presented in the next section.

Preliminary results

Current DT applications are primarily exploratory, utilizing platforms such as Tygron and Cesium, for environmental simulations (e.g., water and heat stress) during early-stage planning. A significant barrier to further formalization of a CBA is the scarcety of empirical, quantitative datasets, as most initiatives are funded through non-recurrent innovation budgets rather than operational cycles that operate long-term. Consequently, the value proposition of DTs currently shifts from direct operational efficiency toward enhanced decision quality and integrated spatial insights. We present the first (conceptual) iteration of the CBA in Table 1 below.

Table 1: Preliminary results of the cost-benefit analysis regarding DT usage.

Category:	CBA Aspect:	Interviewees:	Supporting literature:
Benefits	Failure Cost Avoidance	Central benefit mechanism; reducing costly errors, redesign, and misalignment in later stages.	Mentioned in broader built-environment research, but under-specified in DT CBAs. (Karunaratne et al., 2025; Kookalani et al., 2026; Moshood et al., 2024)
	Temporal Efficiency	Shorter planning timelines leading to lower financing and interest costs.	Some DT case-based reports mention substantial schedule reductions (mainly in construction/infrastructure) (Omrany et al., 2023). Reviews of economic impact also stress that results are highly context-dependent and constrained by integration effort and adoption maturity (Karunaratne et al., 2025)
	Decision Quality	DTs deliver more complete, integrated, and transparent insights.	Frameworks frame value as improved decision support and planning insight (Karunaratne et al., 2025; Lehtola et al., 2022; Peldon et al., 2024).
	Stakeholder Support	Potential for greater public support and understanding.	Visualization can enhance involvement, but raises equity and accessibility concerns (Luo et al., 2025).
Costs	Data Management	Focus on acquisition, quality improvement, and long-term management.	Reviews identify fragmented data ecosystems and connectivity as major barriers (Lei et al., 2023; Mazzetto, 2024).
	Governance	Costs for interdepartmental coordination and multi-actor arrangements.	Implementation is constrained by governance, policy, and privacy requirements (Azadi et al., 2025).
	Infrastructure	Platform licensing and IT infrastructure.	Economic-impact review repeatedly cites high initial investment and integration complexity as obstacles (Karunaratne et al., 2025). Treat infrastructure cost as a major upfront/lifecycle item but not necessarily net-negative if maturity is high (Omrany et al., 2023).
	Capacity	Organizational capacity needed and to run simulations and interpret results.	Reviews note human-factor complexities and socio-technical constraints in DTs which commonly include organizational readiness/capability (Karunaratne et al., 2025; Lehtola et al., 2022; Lei et al., 2023).
Refinements	Temporal Scope	Need for a plan-formation phase before formal design and a benefit review during realization phases, as extra effort in planning (e.g. several simulations) results in large benefits in later area and building realization phases.	Literature describes DT use as supporting planning and design processes; governance/maturity literature analyses how DTs are operationalized in planning processes (often early-stage and iterative) (Dembski et al., 2020).

4 Discussion and Future Work

Our findings indicate that DT value in governmental spatial planning is unlikely to be captured by a narrow financial business case alone. Many relevant costs are lifecycle- and governance-related (data, integration, security, capacity), while many benefits materialize indirectly through improved decision quality and reduced downstream failure costs. This helps explain why DT initiatives often remain pilot-based as downstream results, generated by other organizations, are often not taken into account in pilots. The evidence base required for formal CBA is still limited in practice. The proposed framework contributes by structuring hidden costs and implicit benefits across all process phases and stakeholders, highlighting the distribution of value across municipalities, consultants, developers, users and maintenance organizations. The results suggest a need to reconceptualize IS evaluation of public-sector DTs beyond financial CBA to explicitly incorporate digital governance and public-value measurement. Limitations include the small purposive sample and the largely qualitative nature of reported effects. Next steps are to operationalize key categories into measurable indicators (e.g., failure-cost reduction, redesign frequency, lead-time and financing impacts, stakeholder comprehension) and validate the framework across multiple cases with different governance arrangements. Where monetization is premature, the framework should be complemented with multi-criteria or public-value measures to support transparent decision-making about the use of DT-technology.

Acknowledgments

We would like to thank the experts and organizations that participated in this study for their time and expertise.

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