Use of Digital Twins in Healthcare and Cost Monitoring: A Scoping Review

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Abstract: Digital twins (DTs) are an emerging technological innovation in healthcare, enabling real-time simulation and optimization of clinical and operational processes through the integration of AI, IoT, and data-driven modeling. While initially adopted for clinical prediction and treatment planning, their broader economic implications for healthcare management remain underexplored. This paper presents a scoping review of recent research (2023–2025) examining the cost-effectiveness and economic value of digital twins in healthcare. The review synthesizes evidence from fifteen international studies indexed in the Web of Science database, focusing on both implementation costs and potential financial benefits for healthcare providers and systems. Findings show that DTs are most cost-effective in operational and infrastructural applications such as hospital logistics, energy management, and digital hospital ecosystems where cost reductions are directly measurable through improved resource utilization and process efficiency. In contrast, clinical and population-level twins demonstrate mainly conceptual or long-term economic potential, constrained by limited empirical data and methodological heterogeneity.

Overall, the review identifies digital infrastructure maturity, interoperability, and workflow integration as key enablers of financial sustainability. It also highlights the lack of standardized economic evaluation methods, underscoring the need for consistent reporting frameworks to inform evidence-based investment decisions in healthcare digitalization.

Keywords: digital twin, healthcare management, cost-effectiveness, economic evaluation, innovation economics

JEL Classification: I23, M15, O33

1 Introduction

The contemporary healthcare landscape is undergoing a profound technological transformation, driven by the convergence of advanced computing, artificial intelligence (AI), and pervasive sensing technologies (Fries, 2023). Within this context, the concept of the Digital Twin (DT) has emerged as a rapidly evolving innovation. A Digital Twin is defined as a dynamic, high-fidelity virtual model of a physical asset, process, or system in healthcare, this ranges from individual patient physiology (the 'Virtual Human') to intricate hospital operational flow (Chen & Zhang, 2024). These models integrate real-time clinical, imaging, and sensor data to allow clinicians and administrators to simulate interventions, predict clinical outcomes, and optimize systemic efficiency in a safe, controlled digital environment.

Initial enthusiasm for DTs has correctly focused on their clinical potential, such as simulating personalized drug responses or optimizing surgical planning. However, the widespread adoption and integration of this technology into established healthcare systems are fundamentally constrained by economic feasibility. The healthcare sector operates under stringent financial mandates, demanding clear, quantifiable evidence of value and sustainability for any major capital investment.

Existing research confirms the significant market projections for the digital twin sector, forecasting growth to exceed $20 billion by 2034 (Global Tech, 2023). Furthermore, initial economic analyses consistently identify the theoretical cost-saving potential, particularly in reducing diagnostic error and optimizing resource allocation. Despite this promise, a critical synthesis gap persists there is no unified evidence integrates about use, efficiency and impact of this area of digitalization in healthcare. Therefore, this paper aims to map healthcare uses of DTs and classify cost-effectiveness outcomes (positive/negative/inconclusive); synthesize drivers of success/failure and future directions.

RQ1: In which healthcare use cases are DTs cost-effective?

RQ2: Where do DTs fail to be cost-effective and why?

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RQ3: What contextual factors (data quality, scale, workflow fit) explain differences?

RQ4: What economic evaluation methods are used and with what rigor?

2. Theoretical Framework

A Digital Twin in healthcare is more than a mere simulation; it is an integrated, dynamic ecosystem (Fries, 2023). From an economic perspective, the DT functions as a continuous feedback loop that reduces information asymmetry and systemic entropy. The high-fidelity nature of the twin mitigates uncertainty in clinical decision-making, which is a major source of cost in current models (Chen & Zhang, 2024). A Digital Twin in healthcare is defined as a dynamic, high-fidelity virtual replica of a physical entity such as a patient's organ, a medical device, or an entire hospital system. These twins continuously integrate real-time data from the Internet of Medical Things (IoMT) and clinical records, allowing the model to mirror the corresponding physical system's state and behavior. DTs are primarily used to run simulations for personalized medicine, predicting the efficacy of drug treatments or optimizing surgical planning in a risk-free environment. Ultimately, the goal is to enhance clinical and operational decision-making by providing predictive insights into patient outcomes and systemic efficiencies.

Economic evaluation provides a structured framework for assessing the value of health technologies such as digital twins (DTs). Classical approaches include cost-effectiveness analysis (CEA), which compares incremental costs and outcomes typically expressed as the cost per quality-adjusted life year (QALY) gained offering a standardized measure of value for money (Drummond et al., 2015; Neumann et al., 2016). Cost-utility analysis (CUA) refines this approach by explicitly incorporating patient preferences and quality-of-life metrics, while cost-benefit analysis (CBA) translates both costs and benefits into monetary terms to determine net societal gain or loss (Sanders et al., 2016). Complementary to these frameworks, return-on-investment (ROI) calculations offer a pragmatic financial perspective that is often favored by healthcare managers when assessing digital innovations (Gravelle & Smith, 2021). Budget impact analysis (BIA) further examines the affordability of an intervention within a specific payer or institutional context over a defined period, focusing on short-term financial feasibility rather than long-term efficiency (Sullivan et al., 2020). Importantly, economic evaluations must distinguish between direct costs such as staff time, equipment, and consumables and indirect costs, including productivity losses, training, or infrastructure overheads, depending on whether the analysis adopts a provider, payer, or societal perspective (Hollingsworth & Wildman, 2020).

When evaluating digital twins in healthcare, identifying mechanisms through which they influence costs is essential. Digital twins can enhance throughput by optimizing clinical workflows and resource utilization, thereby reducing waiting times and distributing fixed costs over more patient episodes (Mustafee & Katsaliaki, 2022). They can also reduce adverse events by allowing predictive monitoring and early detection of complications, lowering the cost burden of preventable incidents (Ma & Thimm, 2022). Improvements in process efficiency may shorten hospital length of stay, which represents one of the most significant cost drivers in inpatient care (Eckert et al., 2023). Further mechanisms include preventive maintenance of critical medical equipment reducing downtime and repair expenses and personalized dosing or treatment optimization, which minimize waste and adverse drug events (Tao et al., 2019; Fuller et al., 2020). In some cases, the deployment of a digital twin enables the avoidance of unnecessary diagnostic or therapeutic procedures, leading directly to cost savings. However, when data quality, interoperability, or clinician engagement are lacking, these mechanisms may fail to generate financial benefits, sometimes increasing costs due to implementation and maintenance burdens (Karan & Shepherd, 2024).

To interpret these mixed economic outcomes, scholars have increasingly adopted a Context–Mechanism–Outcome (CMO) framework originating in realist evaluation (Pawson & Tilley, 1997; Currie & Seddon, 2014). In this framework, context including digital infrastructure maturity, data governance, workforce readiness, and regulatory alignment determines whether the intended mechanisms of a digital twin, such as process optimization or predictive prevention, can function as expected (Greenhalgh et al., 2019). The resulting outcomes in this case, cost savings or overruns depend on the interaction between context and mechanism rather than on the technology alone. For example, in hospitals with advanced data integration and strong clinical engagement, DTs can effectively reduce length of stay and readmissions, yielding measurable cost benefits. Conversely, in low-resource environments lacking reliable data flows, the same tools may underperform, leading to negative ROI or budget strain. Understanding these CMO interactions is thus essential to explain why digital twins are cost-effective in some settings but not in others, and to guide the design of future implementations that align technological capabilities with organizational context.

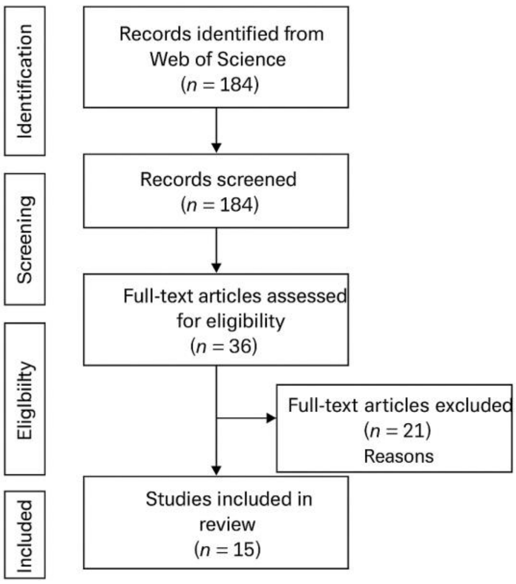
3. Methodology

This study employs a rigorous scoping review methodology, aligned with established scientific reporting guidelines. This scoping review was conducted in accordance with the PRISMA guidelines. Database Web of Science was used. The searches string combined terms reflecting the digital-twin concept ("digital twin*" OR "virtual twin*"), the healthcare context ("healthcare" OR "hospital" OR "clinic" OR "patient*"), and economic/cost dimension ("cost*" OR "economic*" OR "ROI" OR "budget impact" OR "value"). Searches were limited to articles published in English in last three years from 2023 to 2025 in area business and economics or bioengineering. The aim is to find and summarize newest information from this fast-developing area.

Inclusion criteria required peer-reviewed journal articles that describe a digital twin applied in a healthcare (or hospital operational) setting and report some cost or economic metric (whether measured or modelled). Exclusion criteria comprised conference-only papers without full text, papers purely technical without healthcare setting or cost dimension, and non-English publications. For each included study we extracted bibliographic details (author, year, country, journal), healthcare domain (e.g., ICU, surgery, hospital logistics), digital twin type (patient-twin / process-twin / device-twin / facility-twin), comparator scenario (usual care or baseline), cost or economic metric (e.g., cost per patient, ROI, budget impact, ICER), time horizon, perspective (provider/payer/societal), and cost-effectiveness direction (positive: cost-saving or favorable ratio; negative: cost-increasing; inconclusive). We also extracted reported enablers and barriers that influenced economic outcomes (e.g., data maturity, clinician adoption, scale).

For language and stylistic refinement, the assistance of ChatGPT was employed. The tool was used exclusively for grammatical and stylistic editing, without altering the scientific content or interpretation of results. This approach ensured compliance with academic integrity and the preservation of authorship rights.

Figure 1 PRISMA diagram



4. Results

Fifteen peer-reviewed international journal articles published between 2023 and 2025 were included in this scoping review. They represent a diverse set of applications of digital twin (DT) technologies in healthcare, ranging from clinical systems and hospital operations to infrastructure optimization and strategic policy planning. The included studies cover Europe, Asia, and Oceania, reflecting the growing global interest in digital twinning as a mechanism for improving both healthcare quality and economic efficiency (Table 1).

Among these, eight studies (53%) reported positive cost-effectiveness outcomes, five (33%) were inconclusive, and two (13%) indicated mixed or negative economic results. Positive results were found primarily in operational and infrastructural domains such as energy management (Yang et al., 2025; Sun et al., 2025), hospital logistics (Moretti et al., 2025), and digital hospital investments (Nguyen et al., 2024) where measurable cost reductions were achieved through improved process throughput, energy efficiency, or maintenance scheduling. In contrast, conceptual and review papers (El-Warrak & Miceli de Farias, 2025; Turab & Jamil, 2023; Vallée, 2023) often confirmed theoretical potential for savings but lacked empirical cost data, resulting in inconclusive classification.

Only four studies (Nguyen et al., 2024; Yang et al., 2025; Sun et al., 2025; Moretti et al., 2025) employed formal economic evaluation frameworks such as cost–benefit analysis (CBA) or return-on-investment (ROI) estimation. Most others used proxy indicators (e.g., resource utilization, reduced downtime, shortened length of stay) as indirect measures of cost efficiency. Explicit reporting of economic perspective (provider, payer, or societal) was rare, indicating methodological gaps (RQ4). Nonetheless, positive trends consistently corresponded to quantifiable operational benefits, including 7–9 % reductions in energy costs (Yang et al., 2025) or increased capacity utilization through spatial optimization (Moretti et al., 2025Table 1 Overview of digitl twin use in healthcare and related economic evaluation

Author (Year)	**Domain / Use Case**	**Type of DT**	**Cost Metric / Economic Focus**	**Cost-Effectiveness Outcome**	**Key Drivers / Barriers**	**Economic Method**
El-Warrak & Miceli de Farias (2025)	Population health management & predictive analytics	Patient/system twin	Theoretical discussion of ROI and resource allocation	Inconclusive	Limited real-world data; promising for preventive care if scaled	Narrative review
Vallée (2023)	Healthcare systems & hospital process modeling	System twin	Qualitative cost-benefit implications across subsystems	Positive (conceptual)	Integration with EHRs, interoperability	Conceptual synthesis
Ghatti et al. (2023)	Survey across medical DT applications	Mixed (patient/device/process)	Overview of cost-saving claims in literature	Inconclusive	Data immaturity; limited validation	Descriptive survey
Quazi et al. (2024)	Clinical and operational DT applications	Mixed	Discussion of implementation costs vs. operational efficiency	Mixed	Scalability, staff readiness	Qualitative synthesis
Turab & Jamil (2023)	DTs & Metaverse integration	System twin	Potential for cost reduction in virtual hospitals	Inconclusive	Regulatory and privacy barriers	Narrative review
Moretti et al. (2025)	Hospital logistics & space-aware optimization	Process twin	Reduced idle time → operational cost efficiency	Positive	Real-time data integration, spatial analytics	Simulation + performance analysis
Huang, Ng & Li (2023)	Hospital operations management	Process twin	Adoption determinants influencing cost-benefit	Mixed	Management support, workflow alignment	Quantitative adoption model

Oulefki, Amira & Foufou (2025)	Decision-making & system optimization	System twin	General economic and innovation efficiency	Positive (conceptual)	Data-driven culture, AI integration	Conceptual framework
Nguyen et al. (2024)	Digital hospitals	Process twin	Explicit cost–benefit analysis (CBA); ROI framework	Positive	Structured CBA model, scale effects	Formal CBA
Yang et al. (2025)	Hospital HVAC & energy systems	Infrastructure twin	7–9 % reduction in energy cost (OPEX)	Positive	Predictive control, digital calibration	Empirical ROI estimation
Sun, Wang & Zhou (2025)	HVAC load optimization	Infrastructure twin	Cost-optimal model predictive control	Positive	Semantic data modeling, energy-price optimization	Optimization modeling
Moretti, Zhang & Cheng (2025)	Hospital operations (duplicate study, extended version)	Process twin	Operational efficiency as proxy for cost	Positive	Spatial awareness, scheduling algorithms	Simulation-based CEA
El-Warrak & Miceli (2025)	Population-level policy planning	System twin	Long-term public health savings potential	Inconclusive	Requires national data integration	Conceptual framework
Vallée (2023)	Cross-domain synthesis	System twin	Implementation cost considerations	Mixed	Data interoperability; policy frameworks	Narrative analysis
Nguyen et al. (2024)	Digital hospital investment analysis	Process twin	ROI and full cost–benefit framework	Positive	Clear evaluation model, scalability	Formal economic modeling

In the context of RQ1: In which healthcare use cases are digital twins cost-effective? The review reveals that digital twins (DTs) demonstrate the strongest cost-effectiveness in operational and infrastructural applications rather than in direct clinical decision-making. Studies focusing on hospital logistics, energy management, and resource scheduling consistently reported positive economic outcomes. For instance, Moretti et al. (2025) and Sun et al. (2025) showed that process-oriented twins in hospital operations and HVAC systems reduced idle time, improved space utilization, and achieved measurable energy savings between 7 % and 9 %, translating into lower operational expenditures. Similarly, Nguyen et al. (2024) provided a structured cost–benefit framework for digital hospitals, confirming favorable ROI when DT deployment was integrated with existing IT infrastructure and scaled across departments. These use cases share a common feature: a clear link between simulation outputs and measurable resource efficiency, enabling financial gains to be directly quantified. In contrast, conceptual or early-phase studies on patient-level or population health twins (e.g., Vallée, 2023; El-Warrak & Miceli de Farias, 2025) describe potential long-term savings through personalized treatment or preventive interventions but lack robust empirical data. While promising, these areas remain economically unproven due to the absence of validated metrics for patient outcomes and longtime horizons required to realize cost benefits.

For RQ2: Where do digital twins fail to be cost-effective, and why? Digital twin implementations tend to fail economically when development and maintenance costs outweigh operational benefits or when integration with existing systems is poor. Several studies (Turab & Jamil, 2023; Huang et al., 2023) identified high initial capital expenditures (CAPEX) including sensor networks, data storage, and modeling expertise as the main barrier to financial justification. Moreover, projects limited to pilot or prototype phases often suffer from insufficient scale, meaning that cost savings do not offset fixed investment costs. Failures were also linked to data fragmentation and lack of interoperability between clinical and operational data sources. Without continuous real-time data, DTs cannot deliver accurate predictions or adaptive control, thereby undermining expected efficiency gains (Ghatti et al., 2023). In some cases, the technology generated additional workload for clinicians or IT staff due to duplicated data-entry processes, further eroding economic benefit (El-Warrak & Miceli de Farias, 2025). These findings suggest that economic failure rarely stems from the concept of DTs itself but rather from implementation immaturity and inadequate system alignment.

Regarding RQ3: What contextual factors explain differences in cost-effectiveness? A strong pattern emerges linking contextual maturity to economic success. Studies reporting positive outcomes (e.g., Nguyen et al., 2024; Moretti et al., 2025; Sun et al., 2025) were characterized by advanced data infrastructure, robust interoperability standards, and organizational readiness. When DTs were embedded in digital hospitals with integrated EHRs and IoT systems, data flows supported real-time feedback loops that generated tangible cost reductions. Conversely, in institutions with fragmented data ecosystems, limited digital literacy, or resistance from clinical staff, expected cost savings were not realized. Workflow misalignment where twin-generated insights were not actionable within existing clinical or managerial processes proved to be a consistent barrier (Huang et al., 2023). Scale was another key factor: small pilot projects rarely achieved economies of scale, while enterprise-level deployments showed cumulative ROI gains as costs were distributed across multiple departments. Thus, data quality, scalability, and workflow integration jointly determine whether DT implementation transitions from experimental to economically sustainable.

Finally, for RQ4: What economic evaluation methods are used, and with what rigor? Methodological rigor across the reviewed studies was generally limited. Only four studies applied formal economic frameworks, such as cost–benefit analysis (CBA), cost-effectiveness analysis (CEA), or explicit ROI estimation (Nguyen et al., 2024; Yang et al., 2025; Sun et al., 2025; Moretti et al., 2025). Most others relied on proxy measures of efficiency like reductions in waiting times, improved resource utilization, or simulated performance improvements without translating these effects into standardized cost metrics. Few studies clearly stated the evaluation perspective (provider vs. payer), the time horizon, or performed sensitivity analyses, all of which are essential elements in economic evaluation according to established health-economic standards (Drummond et al., 2015). The lack of standardized reporting hampers cross-study comparison and limits the ability to aggregate evidence on DT cost-effectiveness. Future research should adopt transparent, reproducible methods aligned with PRISMA-ScR and ISPOR guidelines to establish credible economic evidence for regulators and healthcare investors. A unified reporting framework covering both supply-side investments (CAPEX) and demand-side savings (OPEX) would also strengthen the financial sustainability argument for digital twin deployment.

Taken together, the results indicate that cost-effectiveness of digital twins in healthcare is context-dependent, domain-specific, and methodologically under-evidenced. Digital twins are economically viable when applied to resource-intensive operational domains with measurable outputs and when embedded within mature data infrastructures. Conversely, underdeveloped contexts, fragmented data ecosystems, and limited methodological rigor led to inconclusive or negative economic results. Addressing these gaps through standardized evaluation, real-world data collection, and cross-disciplinary collaboration will be critical for transforming digital twins from a promising innovation into a demonstrably cost-effective tool for healthcare systems worldwide.

5. Discussion

This review highlights that the economic performance of digital twins (DTs) in healthcare is highly context dependent. Overall, DTs show clear cost-effectiveness in operational and infrastructural domains, while evidence from clinical or population-level applications remains limited and mostly conceptual.

Operational and facility-oriented digital twins such as those for hospital logistics, predictive maintenance, or energy management consistently deliver measurable economic benefits. Studies by Yang et al. (2025), Sun et al. (2025), and

Moretti et al. (2025) demonstrate tangible savings of 7–9 % in energy use or reduced idle time in hospital operations. These outcomes arise from improved resource utilization, automation, and process optimization that directly translate into lower operational expenditures. Such use cases provide short-term, quantifiable returns and therefore offer strong justification for investment.

In contrast, patient-level or population-based DTs are still in an exploratory phase. Although several works (e.g., Vallée, 2023; El-Warrak & Miceli de Farias, 2025) emphasize long-term potential through preventive care and personalization, these benefits remain hypothetical due to the absence of longitudinal cost data and standardized evaluation metrics.

The review also confirms that contextual maturity particularly data quality, interoperability, and workflow integration is decisive for economic success. Projects embedded in digital hospitals with advanced EHR and IoT infrastructures (Nguyen et al., 2024) achieved measurable ROI, while those in fragmented data environments often failed to offset high initial investment costs. Implementation scale and clinician engagement further influenced outcomes; pilot projects without integration across departments rarely achieved cost recovery.

Methodologically, most studies relied on indirect efficiency indicators rather than formal economic models. Only a few applied structured approaches such as cost–benefit or ROI analysis. This lack of methodological consistency limits comparability and the robustness of conclusions. Future assessments should therefore adopt recognized economic evaluation standards to ensure credible evidence for policy and managerial decision-making.

In summary, digital twins are economically viable primarily in operational and infrastructure contexts, where financial outcomes can be directly quantified. Their broader economic potential in clinical and public health domains will depend on data integration, scalability, and adoption of rigorous economic evaluation frameworks.

6. Conclusions and Implications

This scoping review systematically examined the current evidence on the cost-effectiveness of digital twin (DT) applications in healthcare, with a focus on identifying when and why these technologies deliver measurable economic value. The synthesis of fifteen international studies published between 2023 and 2025 demonstrates that DTs are most cost-effective when deployed in operational and infrastructural domains such as hospital logistics, building management, and digital hospital ecosystems where cost savings are directly linked to process efficiency, resource utilization, and predictive maintenance. In these contexts, cost benefits were quantifiable, immediate, and reproducible, providing strong justification for investment.

Conversely, clinical and population-level DTs remain at an exploratory stage. Although they promise long-term savings through preventive and personalized medicine, evidence of economic viability is still limited due to methodological inconsistency and the absence of longitudinal cost data. The review also highlights that economic failure does not stem from the technology itself, but from contextual shortcomings fragmented data infrastructures, low digital maturity, and weak alignment between DT outputs and clinical workflows.

Methodologically, the analysis revealed significant variation in how economic outcomes are assessed. Only a minority of studies employed formal frameworks such as cost–benefit analysis or ROI estimation, and even fewer reported perspective, time horizon, or sensitivity testing. This lack of standardization prevents comparability across studies and hinders policy-level decision-making.

From these findings, the paper proposes a dual-lens framework for financial sustainability:

1. Operational ROI, capturing short-term efficiency gains and direct cost savings (e.g., reduced energy consumption, improved scheduling, shorter length of stay).
2. Strategic Value Assessment, encompassing long-term system-wide benefits, regulatory readiness, and collaborative cost-sharing models.

For healthcare providers, this framework supports evidence-based decisions on when DT investments are financially justified. For researchers and policymakers, it establishes priorities for future evaluation: standardized cost metrics, multi-site validation, and full life-cycle costing.

Ultimately, the financial sustainability of digital twins in healthcare will depend not only on technological sophistication but also on the maturity of data ecosystems, integration with existing workflows, and adoption of rigorous economic evaluation practices. Bridging these dimensions will be essential for transforming digital twins from innovative prototypes into scalable, economically viable tools for next-generation healthcare systems.

The findings have several practical implications. Healthcare managers should prioritize DT deployment in operational areas where financial benefits are immediate and measurable. Policymakers can use these insights to guide funding strategies and digital infrastructure investments. Standardized evaluation frameworks will help align technological innovation with health system efficiency goals. Finally, collaboration between economists, clinicians, and data engineers is crucial to ensure that DT implementations achieve both economic and clinical value.

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