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Integrating digital twins and decision support systems for predictive risk management in urban renewal

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ABSTRACT

Urban renewal projects are increasingly central to addressing rapid urbanisation, deteriorating infrastructure, and climate-induced vulnerabilities. However, they are characterised by complex and interdependent risks spanning structural, socio-economic, environmental, and managerial domains that remain poorly managed by conventional methods. While digital twin (DT) technology has demonstrated value in construction monitoring, predictive maintenance, and safety management, its application as an integrated framework for risk management in urban renewal remains underdeveloped. This study addresses this critical gap by developing a DT-enabled decision support system tailored for risk management in urban renewal construction. Scopus database for peer-reviewed publications from (2014–August 2025) was used, synthesising evidence from 47 peer-reviewed studies that met the inclusion and exclusion criteria guided by PRISMA methodology for systematic review process. Findings reveal that existing DT applications are fragmented, focusing on isolated risks rather than adopting a holistic perspective on urban renewal challenges. To overcome this limitation, a comprehensive conceptual framework that integrates DT technology with decision support systems, enabling real-time monitoring, predictive risk modelling, and proactive decision-making across the full project lifecycle was proposed. The framework demonstrates novelty of this research by bridging structural, environmental, and socio-economic risks, offering a multi-dimensional approach to urban futures resilient through DTs potentials.

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Digital twin; construction risk management; urban renewal; building resilience

Urban renewal construction initiatives are becoming increasingly vital to accommodate expanding populations, enhance urban resilience, and rejuvenate ageing infrastructure [1]. Yet these projects are inherently complex and expose multiple stakeholders to overlapping risk domains social displacement, financial uncertainty, environmental hazards, and management challenges [2,3]. Traditional risk-management approaches relying heavily on historical data, expert judgement, and reactive strategies struggle to keep pace with the dynamic, multidimensional nature of these risks. Consequently, project delays, cost overruns, and compromised safety outcomes often follow [4].

In recent years, digital technologies have emerged as potential remedies to some of these shortcomings. Among these, the concept of a ‘digital twin’ (DT), a dynamic virtual replica of physical assets maintained through real-time data input, has shown promise in domains such as predictive maintenance, performance monitoring, and safety management [2,5]. In parallel, decision support systems (DSS) have matured, enabling data-driven decision-making in construction by integrating analytics, modelling, scenario evaluation, and optimisation [6].

Despite the individual traction of DT and DSS, their combined application as a comprehensive risk-management framework in urban renewal remains limited and fragmented. The current state-of-the-art

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reveals that most DT deployments focus on discrete issues safety risk simulations, facility-management optimisation, or predictive maintenance of individual assets [2,5]. These efforts reveal potential, but they fall short of developing frameworks that capture the full complexity of urban renewal risks, especially the interaction among socio-economic, environmental, and structural domains [7]. Moreover, the majority of existing models emphasise reactive or post-event strategies, rather than proactive or predictive governance [8]. Indeed, although DTs in the built-environment context excel at monitoring, anomaly detection, and predictive maintenance, their applications remain largely confined to single-risk domains, dashboard-centred visualisations, and weak coupling to explicit decision rules or optimisation logic [2]. In the context of urban renewal, where technical, environmental, and social risks are intricately intertwined, this fragmented approach constrains the potential for proactive governance.

This paper addresses these gaps by posing the following research question: How can a Digital Twin-enabled Decision Support System enhance risk management in urban renewal construction projects?

The goal of this study is threefold:

1. To identify and classify key risk factors in urban renewal construction through a systematic review.
2. To evaluate existing DT applications in construction risk management and assess their limitations.
3. To propose a novel, integrated DT-enabled framework that unites risk domains, enhances predictive capability, and supports resilience and sustainability in urban renewal.

By explicitly linking DT technology with risk-sensitive urban renewal, this study offers novel insights into the governance of construction risk. Unlike prior studies that address risks in isolation, our approach offers a holistic, decision-oriented framework. The contribution lies not only in theory-building, advancing DT integration as a mechanism for resilience, but also in practice, providing construction managers with a tool for data-driven, proactive, and sustainable decision-making.

1. Literature review

1.1. Digital twin technology in construction

The concept of a Digital Twin (DT) marks a paradigm shift in the management, optimisation, and understanding of physical assets and processes. At its core, a DT is a dynamic digital replica of a physical object, system, or process, continuously updated via data integration from sensors and Internet of Things (IoT) devices [9]. This definition moves beyond static modelling by enabling synchronisation of the physical and virtual domains, creating a feedback loop in which the digital counterpart not only reflects current conditions but can also predict future states. The theoretical foundations of DTs were first articulated by Grieves and Vickers [10] who envisioned them as a bridge connecting physical and digital worlds. Over time, these ideas have been enriched by advances in simulation, machine learning and analytics, positioning DTs as powerful enablers of predictive and prescriptive decision-making.

In construction contexts, DTs have been deployed to track structural element performance, providing instant feedback on stress distribution, material degradation, and other hidden vulnerabilities is especially relevant to urban renewal projects with ageing infrastructure [11]. By linking design, construction, and operation phases seamlessly, DTs foster integrated project delivery, reduce errors, minimise rework, and enhance both efficiency and resilience [12]. A defining strength of DTs lies in their capacity to run ‘what-if’ simulations, testing alternative design or management strategies under different conditions; this ability to anticipate and adapt to uncertainty is especially critical in the high-risk domain of urban renewal, where structural safety, environmental variability, and socio-economic impacts all intersect [13].

However, review studies in the construction domain still consider DT deployment to be relatively nascent. For instance, a comprehensive review identified eight implementation areas (virtual design, planning, asset management, safety, energy, quality, supply chain, structural health) but highlighted major barriers such as data integration, interoperability, scalability, security, and standards [14]. This indicates both the promise of DTs and the substantial gap between concept and full practice (Figure 1). The figure presents a multi-level taxonomy of digital twins in the built environment, from component-

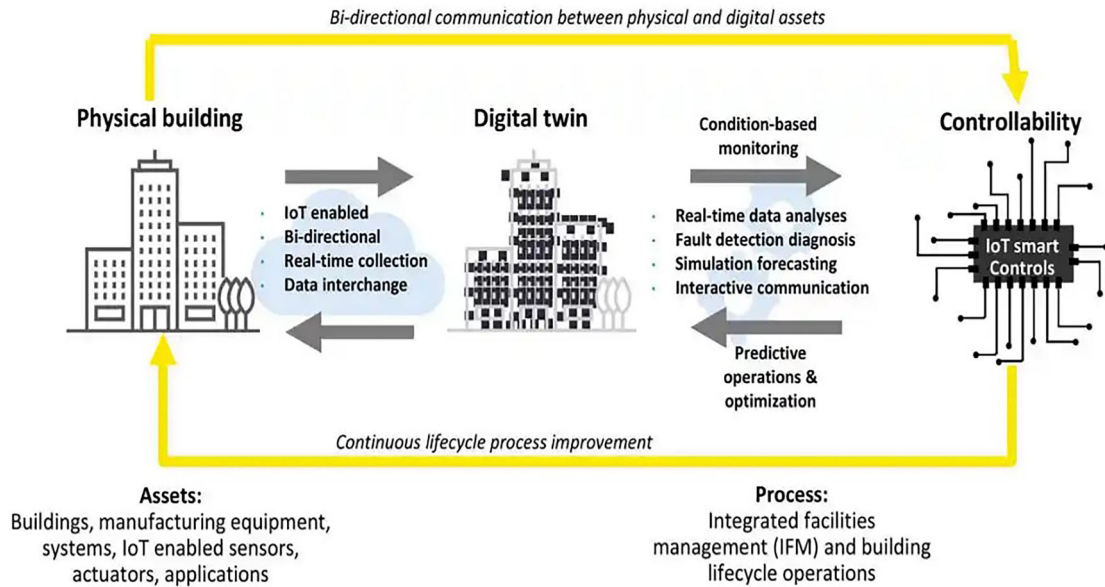


Figure 1. Definition and conceptual foundations [14].

level twins (e.g. individual HVAC or structural elements) through to asset-level (entire building) and process/portfolio-level twins (multi-asset management, supply-chain or real-estate portfolios). The diagram further illustrates how a digital twin combines: (i) spatial and semantic data (e.g. geometry, BIM/IFC), (ii) real-time sensor/IoT operational data (environment, structural state, usage), and (iii) analytics/simulation layers to form a living digital representation. This living twin supports four key value-propositions: maintenance & operations, environmental sustainability, occupant health & wellness, and real-estate/people-centred optimisation. In doing so, DT transcends static digital models, enabling continuous monitoring, predictive maintenance, adaptive optimisation, and human-centric building management.' Building on this foundation, this study extends the concept by embedding multi-domain risk logic and decision workflows, thereby transforming the digital twin from a monitoring dashboard into a full-scale decision infrastructure tailored for risk-sensitive urban-renewal governance.

1.2. Overview and evolution of decision support systems (DSS) in construction management

Decision Support Systems (DSS) in construction have evolved substantially over decades from simple spreadsheet- and rule-based tools to complex, data-driven, and dynamic frameworks that increasingly integrate real-time data, information modelling, and predictive capabilities. In the early days, DSS in construction tended to be rule-based tools, spreadsheet calculators, and simple expert systems intended primarily for tendering, scheduling, and budgeting tasks [15]. These systems provided basic decision support but were largely descriptive, isolated, and siloed, focusing on discrete project tasks rather than offering holistic or integrated risk governance across a project's lifecycle [15]. As the complexity of construction projects rose with larger scale, tighter schedules, multi-stakeholder involvement and increased uncertainty the limitations of these early DSS became evident. To address trade-offs between cost, time, quality, and risk, the sector saw a shift towards Multi-Criteria Decision Making (MCDM) methods such as the Analytic Hierarchy Process (AHP), TOPSIS, VIKOR and other optimisation-based techniques [16]. These methods allowed decision makers to evaluate multiple conflicting objectives and choose compromise solutions, improving rationality and transparency in decision-making processes.

With the advent and widespread adoption of Building Information Modelling (BIM), DSS began to integrate richer semantic, spatial and temporal information. BIM, especially when extended to 4D (time) and 5D (cost + time + resources) models, enabled planners and managers to visualise construction sequences, cost flows, and resource allocation in a unified digital model of the building. This shift transformed DSS from retrospective or tabular planning tools into more proactive planning aids combining geometry, schedule, cost, and risk parameters [17,18]. Building on BIM and advances in data

acquisition technologies, the more recent frontier of DSS involves knowledge-based, data-driven systems where real-time data from IoT sensors, site monitoring, environmental sensors, resource tracking, and other sources feed directly into decision-support logic [19]. These advanced systems support sensing → inference → scenario-testing → action loops, enabling dynamic updates of project status, risk assessments, and prompt interventions [19].

For instance, one recent work demonstrates how a BIM-based DSS, combined with real-time data (progress measurements, probabilistic scheduling, and resource use), can visually detect critical activities, monitor risky tasks subject to delay, and categorise delayed activities thereby supporting probabilistic duration estimation and proactive risk mitigation [20]. Another study highlights that DSS adoption in construction is increasingly informed by Industry 4.0 technologies like AI, machine learning, IoT and digital-twin paradigms, indicating a trend towards more intelligent, adaptive decision infrastructures that handle uncertainty, complexity, and real-world variability [21]. Yet despite these advances, recent reviews show that many existing DSS remain limited in scope. They typically address specific phases (often construction), or focus only on some aspects (cost, schedule, safety), rather than providing full-lifecycle, integrated, multi-risk decision support [19]. Moreover, while integration between BIM and real-time data is increasingly advocated, work combining BIM, IoT, live data streams and decision-logic (i.e. ‘digital twin-based DSS’) remains rare, and full realisation (with closed-loop sensing, inference and action) is even more limited. This gap sets the stage for frameworks like the one proposed this study aim to attempt to formalise risk propagation, lifecycle governance, real-time monitoring and decision coupling. In summary, the evolution of DSS in construction shows a clear trajectory: from static, rule-based assistance towards dynamic, data-driven, knowledge-based decision infrastructures.

1.3. The urban renewal and risk management context

Urban renewal construction projects are characterised by a constellation of risks that span structural, environmental, and socio-economic dimensions. Structural risks often stem from material deterioration, outdated codes, and hidden vulnerabilities in ageing infrastructure [22]. Environmental risks such as air pollution, urban heat-island effects, and climate change-induced hazards, further complicate renewal efforts [23]. Adding to this complexity are socio-economic risks: community displacement, resistance to redevelopment, and equity concerns, which undermine project acceptance and sustainability [24].

What makes urban renewal particularly complex is the interdependence of these risk domains. Addressing them in isolation, as much of the existing literature tends to fail to capture their cascading effects [25]. For example, structural deterioration may amplify environmental vulnerability, while inadequate community engagement can exacerbate socio-economic tensions. This fragmented approach limits the capacity of conventional risk-management frameworks to provide comprehensive and adaptive responses. Traditional approaches largely rely on expert judgement, historical data, and reactive measures, and they lack the agility to anticipate emerging risks in real-time [26]. As a result, projects frequently suffer delays, cost overruns, and safety incidents symptomatic of an over-reliance on post-event responses rather than proactive strategies [27].

Herein lies the transformative opportunity: integrating DT and DSS offers potential for a unified, data-driven perspective of structural, environmental, and socio-economic risks, enabling anticipatory rather than reactive interventions [28]. This aligns with the broader urban governance concept of risk-sensitive urban development proposed by UN-Habitat, which advocates embedding risk assessments into the planning and design of cities [29]. By leveraging DTs within risk-sensitive planning, urban growth can be directed towards safer, adaptive, and sustainable built-environments, ensuring renewal does not simply reproduce existing vulnerabilities [30,31].

1.4. Conceptual framework for integrating DT and DSS for risk management

The convergence of DT technology and DSS platforms represents a transformative advancement in construction risk management, especially within the complex domain of urban renewal. While DTs provide real-time digital replicas of physical assets continuously enriched via sensor and IoT data, DSS

platforms bring advanced analytics, modelling, and simulation capabilities to extract meaning from these data streams. When integrated, they form a continuous feedback loop in which physical conditions are monitored, risks are modelled, and decision-makers receive predictive insights and actionable recommendations [32].

This synergy moves beyond traditional risk management, characterised by perceptions of static and reactive practice, by enabling anticipatory governance of risks. Real-time monitoring via DT ensures structural, environmental, and socio-economic vulnerabilities are captured in evolution. Simultaneously, the DSS component translates this data into scenario-based forecasts and adaptive strategies. Such integration enables dynamic adjustments across the lifecycle of a project from design and planning through execution and maintenance, empowering managers to proactively mitigate risks before they escalate.

The distinct advantages of a DT–DSS framework include:

- Enhanced accuracy in risk forecasting through continuous data-driven modelling;
- Proactive decision-making supported by predictive analytics rather than post-event responses;
- Lifecycle integration enabling risk-sensitive management from project conception to decommissioning;
- Resilience-building capacity embedding ‘what-if’ simulations to evaluate different interventions under uncertain conditions.

Despite this transformative potential, the integration of DTs with DSS also presents critical challenges. Notably, interoperability issues (heterogeneous data formats, divergent standards) often hinder seamless exchange across platforms [30,33]. Cyber-security risks further complicate adoption-sensitive urban renewal data require robust protocols to prevent breaches and misuse. Additionally, high capital costs and infrastructural demands associated with advanced DT–DSS deployment limit scalability especially in resource-constrained environments [31,34]. Taken together, this conceptual framework underscores the need for standardisation, cross-platform interoperability, and secure digital infrastructures to realise the full potential of DT–DSS integration. If systematically addressed, the framework offers not just a technical pathway but a strategic mechanism for proactive, resilient and sustainable risk management in urban renewal construction.

1.5. Identified gaps in the literature

A critical synthesis of the existing literature reveals three interrelated gaps that this study seeks to address:

1. Although DTs are increasingly deployed in construction for applications such as safety monitoring, predictive maintenance and facility management, their systematic integration with DSS for the purpose of urban renewal risk management remains under-explored [35].
2. Current approaches are fragmented and domain-specific, frequently addressing isolated risk factors (e.g. structural degradation or socio-economic displacement) without recognising the interdependencies among structural, environmental, and social risk domains. Such siloed perspectives restrict the ability of existing frameworks to provide context-sensitive, holistic solutions [36].
3. Prevailing risk-management strategies in urban renewal remain predominantly reactive, relying on historical data and post-event interventions. There is limited research leveraging predictive analytics, real-time monitoring or anticipatory simulation to proactively identify and mitigate risks before escalation [26,28].

Taken together, these gaps reveal the absence of a holistic, forward-looking framework capable of addressing the multidimensional, interdependent and dynamic nature of urban renewal risks. This study responds by advancing a DT-enabled DSS (DT–DSS) framework. The proposed framework unifies fragmented approaches, integrates structural, environmental and socio-economic dimensions of risk, and embeds predictive capabilities into the decision-making process. In so doing, it contributes a novel conceptual model to the literature and also offers construction managers and policymakers a

practical tool for comprehensive, real-time and resilience-oriented risk management in urban renewal construction.

2. Research methodology

The methodical approach used to examine the incorporation of DT technology into decision support systems (DSS) for construction risk management in urban renewal projects is outlined in this section. Following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines, this study identifies frameworks, drivers, and barriers for DT-enabled risk mitigation in urban renewal contexts by synthesising literature from the Scopus database. Four steps make up the methodology: (1) choosing a database and creating a search query, (2) identifying the study, (3) applying the exclusion criteria, and (4) screening and analysis. To improve transparency and reproducibility, visual aids such as a keyword co-occurrence network, a PRISMA flow diagram, and annual publication trends are used.

Database and Search Query: To ensure a comprehensive coverage of peer-reviewed literature in engineering, construction and urban studies, the Scopus database was selected. The search query was constructed to intersect four thematic clusters: Digital Twin technologies, construction risk management, urban renewal processes, and building resilience or sustainability concepts. The query was applied to the Title, Abstract, and Keywords fields of Scopus-indexed articles published between 2010 and 2024. Specifically, the Boolean logic used was: (G1-G4 below):

Search Query: ('Digital Twin*' OR 'DT') AND ('Construction Risk Management' OR 'Risk Management' OR 'Risk Mitigation') AND ('Urban Renewal' OR 'Urban Redevelopment' OR 'Urban Regeneration') AND ('Building Resilience' OR 'Building Sustainability' OR 'Building Information Modelling'). The query was applied to the title, abstract, and keywords of Scopus-indexed articles published between 2010 and 2024. To refine relevance, the logical structure (G1) AND (G2) AND (G3) AND (G4) was adopted, where:

G1: Digital Twin terms (e.g. 'Digital Twin,' 'DT,' 'Cyber-Physical System').

G2: Risk management terms (e.g. 'Construction Risk,' 'Risk Assessment').

G3: Urban renewal terms (e.g. 'Urban Renewal,' 'Redevelopment').

G4: Building resilience terms (e.g. 'Resilient Infrastructure,' 'BIM').

2.1. Study identification

2.1.1. Step 1: Database search

The systematic review was conducted exclusively on the Scopus database. The search query was applied to the 'Title,' 'Abstract,' and 'Keywords' fields to maximise retrieval accuracy. The query captured articles where the key terms appeared in any of these fields, ensuring that studies from multiple perspectives ranging from theoretical models to applied case studies were identified.

Timeframe: Articles published between 2014 and April 2025 were included.

Initial Records: As of the search date, the query returned approximately 3,200 records.

2.1.2. Step 2: Exclusion criteria

To refine the data synthesis, the following exclusion criteria were applied:

Language: Only articles published in English were considered.

Publication Type: The search was limited to peer-reviewed journal articles and conference proceedings, as these provide the highest research quality.

Duplicate Removal: Duplicate records were identified and removed. After de-duplication, the corpus was reduced to around 2,500 unique records.

Subject Relevance: Articles not relevant to the intersection of DT technology, construction risk management, urban renewal, and building resilience were excluded based on title and abstract screening.

2.1.3. Step 3: Screening process

A two-tiered screening process was employed:

Title Screening: Articles whose titles clearly did not address the application of DT in urban construction risk management were removed. This phase excluded studies that were out of scope (e.g. those solely focused on DT applications in unrelated fields such as healthcare).

Abstract Screening: The remaining records underwent abstract screening to confirm that each study engaged with at least one of the core aspects of DT, construction risk, urban renewal, or building resilience. Studies that did not address these interrelated topics were discarded.

The screening process was documented and is visually represented in a PRISMA flow diagram (Figure 2).

After this rigorous screening process, 47 articles were deemed relevant for further analysis.

2.2. Data extraction and analysis

2.2.1. Data extraction

For each of the 47 selected studies, key information was extracted, including:

Bibliographic Details: Author(s), year of publication, and journal/conference.

Study Focus: Whether the study addressed DT technology, construction risk management, urban renewal, or building resilience.

Methodological Approach: The research methods used (e.g. empirical study, simulation, case study).

Key Findings: Insights on risk factors, decision support capabilities, and DT integration.

A data extraction template was used to ensure consistency and to facilitate cross-comparison among studies.

2.2.2. Data synthesis

The extracted data was synthesised using both qualitative and quantitative methods. Descriptive statistics (e.g. annual publication trends) were generated to provide an overview of research activity over time. Figure 3 presents the annual publication trends on the subject, derived from databases. The dark blue lines show the frequency of the article derived per year, showing a spike from 2020 to the year 2024. 2025 showed a decline, which is due to a few months of coverage within the year. The dotted line shows the trendline of the publication. Figure 4 shows the type of article employed in the study; a larger percentage was a journal publication.

Furthermore, thematic analysis was conducted to identify common risk factors, DT implementation challenges, and decision support strategies. This qualitative synthesis was supported by a content analysis of keywords.

2.3. Co-occurrence network analysis

To visualise the interrelationship among keywords, a co-occurrence network was generated using VOSviewer. The network was constructed with a minimum occurrence threshold set at four. This analysis highlights clusters of frequently co-mentioned terms, revealing dominant themes such as ‘Digital Twin,’ ‘Risk Management,’ ‘Urban Renewal,’ and ‘Building Resilience (Figure 5).’

3. Analysis of findings

3.1. Characteristics of the study

A total of 47 articles were relevant for the systematic review, with the first publication in 2016. Across 2014–August 2025, the sourced article is dominated by peer-reviewed journal articles, complemented by conference papers. About half are systematic/bibliometric reviews and roadmaps on Digital Twins in construction, safety, and urban renewal. Roughly one third propose conceptual or architectural frameworks (e.g. CDT, RDT, DT-BIM), and a smaller subset report empirical pilots or field case studies. Typical data sources span BIM/IFC models, safety wearables and proximity sensors, environmental

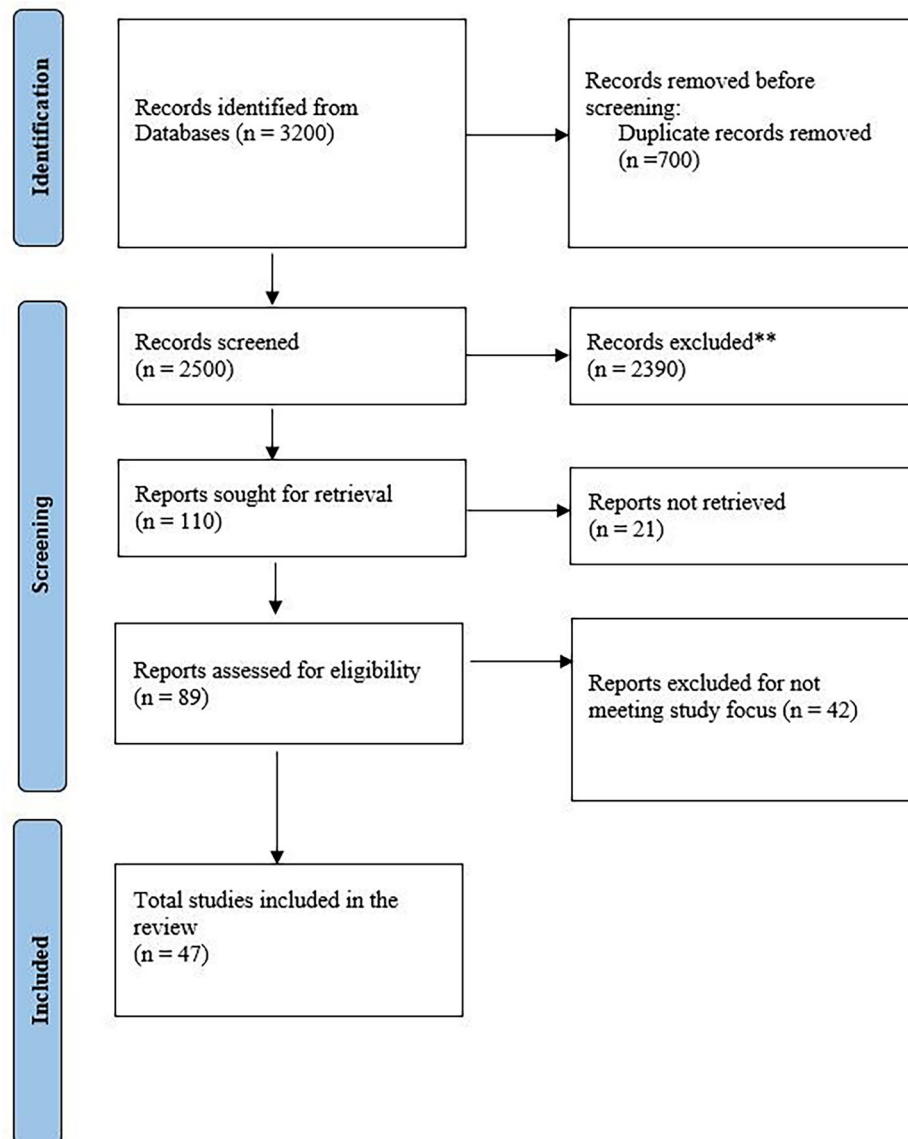


Figure 2. PRISMA flow diagram.

This diagram tracks the number of records identified, screened, excluded, and finally included in the review, mirroring the structure in the attached methodology.

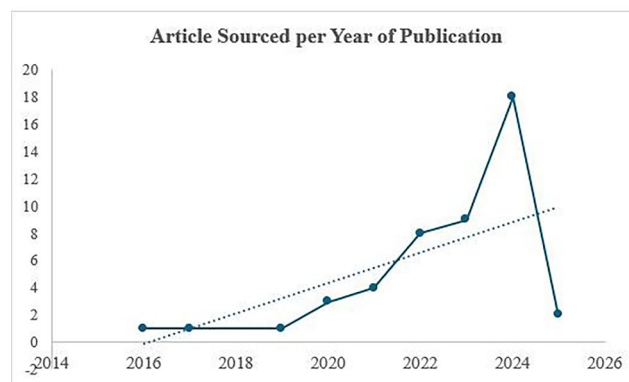


Figure 3. Annual publication trends.

This bar graph depicts the number of publications per year from 2015 to 2025 August, similar in style to the attached paper's trend analysis.

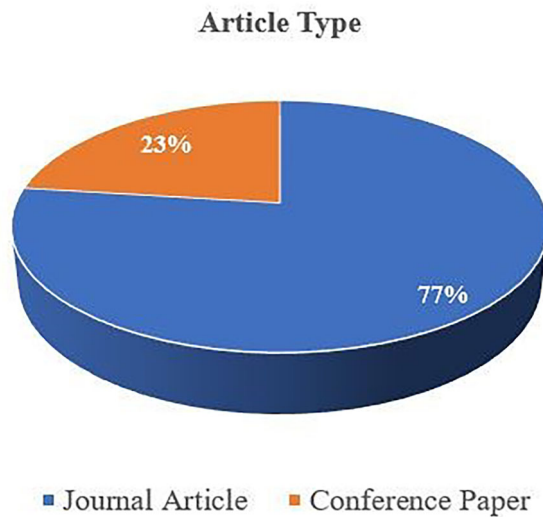


Figure 4. The type of article in the study.

The chart indicated the types of articles sourced; over half of the articles are journal publication.

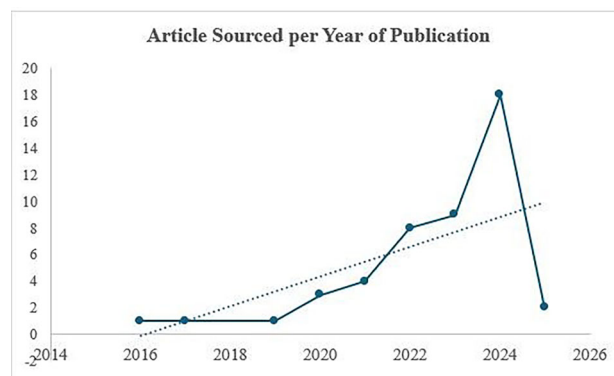


Figure 5. Co-occurrence network of keywords.

monitors (dust, noise, microclimate), schedule/cost systems, and stakeholder records. Decision capabilities progress from dashboards and threshold rules to Bayesian risk propagation and multi-criteria ranking; however, full closed-loop, on-site validations remain limited.

The corpus spans four main journal outlets. First, Digital Twin is a rapid, open-research platform (published by Taylor & Francis) with open peer review and data-sharing focus across sectors, including smart city and AEC applications. Second, construction/project-management outlets such as Engineering, Construction and Architectural Management (Emerald) emphasise integrated design-construction practice and management science. Third, sustainability/built-environment OA journals (MDPI) like Sustainability and Buildings publish broad, applied work on urban sustainability and building science. Fourth, technical engineering journals (Elsevier) including Sustainable Cities and Society, Journal of Building Engineering, and Automation in Construction specialise in urban systems, building engineering and AEC automation (mostly hybrid OA). This mix shows DT research cutting across open-access platforms, management venues, and high-impact technical journals, reflecting its interdisciplinary uptake.

3.1.1. RQ1: What are the key risk factors in urban renewal?

Urban renewal projects encompass social, financial, environmental, and managerial uncertainties that emerge during planning, demolition, construction, and handover. Recent reviews indicate that Digital Twin (DT) approaches surpass static risk registers by integrating live data (sensors, models, stakeholder inputs) with simulation and decision rules, thereby enabling continuous risk monitoring, stress-testing ‘what-if’ options before action, and reducing schedule and cost losses [2,3,5]. In practical terms, DTs

Table 1. Publications on risk factors in urban renewal.

Risk factors	References
Social	[3,34,35,36]
Financial	[11,37,38,39]
Environmental	[40,41,42,43,44]
Management	[12,22,45,46]

couple site telemetry and project-control data to explicit decision logic, for example, flagging early-warning thresholds, recomputing multi-criteria trade-offs, and documenting auditable triggers for intervention rather than acting as descriptive dashboards alone [12,33] (Table 1).

Social and stakeholder risk remains a highly visible domain in urban renewal, especially where demolition, relocation and compensation processes are executed under weak transparency and limited public participation. Large-sample studies of urban regeneration in China identify unfair compensation and inconsistent resettlement practices as the strongest social-risk drivers, frequently amplifying grievances, protests and schedule disruption when information disclosure and participation are weak [34,35]. These consequences are not just delays, they also reduce stakeholder trust and impair project legitimacy. Within a DT-enabled decision-support workflow, such social-risk drivers can be translated into measurable operational indicators: for instance, compensation progress versus plan, grievance volumes and average resolution times, relocation-milestone adherence, and stakeholder participation coverage [36]. When thresholds (such as grievance incidents per week) are crossed, pre-arranged triggers (for example, re-phasing demolition or revising compensation offers) can be activated. Thus, the workflow bridges the gap between qualitative social concerns and quantitative decision-logic moving beyond the static risk register to a live, auditable mechanism [25,33].

Financial risk cuts across cost growth, funding gaps, and cash-flow fragility of which are well-established causes of delay and abandonment in renewal programmes. Systematic reviews show clear links between cost escalation and scope change, estimation error, supply-chain shocks, and weak contract management drivers, particularly acute in developing contexts and complex urban works [37,38]. The literature on abandoned or incomplete public renewal projects repeatedly ranks inadequate funding and poor budgeting among the top causes of failure, alongside planning discontinuities across political cycles [11,39]. A DT-supported decision process makes these financial risks more observable and actionable early in the delivery cycle by tracking metrics such as earned-value indices (Schedule Performance Index, Cost Performance Index), change-order velocity, procurement lead times, and commodity-price indices [38]. Moreover, by incorporating these into simulation or ‘what-if’ routines (e.g. ‘if SPI < 0.9 for two successive periods → initiate value-engineering’), the system helps decision-makers test alternative sequences or value-engineering options before committing to irreversible trades, thereby reducing exposure to downstream cost and schedule losses.

Environmental and climate risk arises in urban renewal when redevelopment intensifies pressures on heat, air quality or drainage infrastructure. Empirical work shows that renewal typologies and altered urban form can exacerbate urban-heat-island intensity and micro-climatic stress if greening and shading are mishandled [40,41]. Urban waterlogging is another recurrent risk during both construction and operation phases, where drainage capacity, increased imperviousness and extreme rainfall interact; recent models quantify water-logging susceptibility and show how infrastructure gaps drive ponding and disruption [42,43]. A DT enables such exposures to become tractable: for example, by integrating IoT sensors (dust/air-quality/meteorology), satellite thermal imagery, drainage/BIM models and hydrologic sensors to test ‘what-if’ interventions (e.g. porous-paving, additional shading, re-sequencing staging) and to trigger temporary mitigation measures (such as adjusting work-hours when rainfall thresholds are exceeded) [44]. This elevates environmental risk from a latent planning concern to a continuously monitored and decision-enabled domain.

Management and organisational risk are heightened in urban renewal because these works are often executed in live, constrained or heritage contexts. Such contexts demand tight coordination, high-skill supervision, disciplined materials, and document control. Studies of construction in revitalised or historic districts show that preservation constraints, dense urban settings, and multi-party governance increase the likelihood of clashes, delays, and re-work unless planning and capability are strengthened

[22,45,46]. Broader supply-chain reviews identify interoperability and coordination risks that ripple through lead times and site productivity [47]. Within the DT-DSS paradigm, these management risks map into operational metrics such as BIM/IFC-model clash counts, RFI/submittal backlog durations, late-delivery telemetry, and site-productivity indices. The system can simulate alternative sequencing when thresholds are exceeded, surface conflicts early, log decisions for accountability, and reduce the latency between detection of an organisational risk and corrective action [12].

Collectively, the literature establishes that the dominant risk families in urban renewal social, financial, environmental and managerial are not only well-documented but also each amenable to operationalisation via DT-enabled decision workflows. Each risk domain aligns naturally to observable indicators and pre-agreed decision-trigger rules. By explicitly coupling live indicators with probabilistic risk propagation and auditable triggers, the proposed DT-enabled framework addresses a known weakness in prior work namely the gap between descriptive monitoring and timely, auditable intervention [25,33]. Thus, the contribution of this study lies in mapping risk domains $\rightarrow$ indicators $\rightarrow$ decision logic, presenting an integrated, multi-domain risk governance model tailor-made for urban renewal contexts.

3.1.2. RQ2: What are the current DT applications in construction risk management?

Across the project lifecycle, Digital Twins are moving construction risk management from periodic, paper-based assessments to continuous, data-driven supervision that couples sensing with simulation and explicit decision rules. Contemporary syntheses describe DTs as a live, computational mirror of construction processes and assets, connecting field telemetry, design/4D models and analytics so that risks are detected earlier, ‘what-if’ options are trialled virtually, and interventions are justified with auditable evidence [7,31,33]. In practical terms, the shift is from descriptive dashboards to decision-centred workflows where alerts, risk estimates and ranked responses are generated in near real time. This section summarises how that shift is already materialising in today’s applications [2,28].

Real-Time monitoring and data acquisition. Design, construction, and supervision firms can employ DT models to manage projects and share information in real time [48]. This, in turn, helps to manage risk during the project. This initiative also helps to foresee risks before they take place in a project, which brings about safety and proper execution of the construction project [24]. Real-time data collection, transfer, analysis, and utilisation for better decision-making towards intelligent facility management are made possible by digital twins (DT) [49]. Reviews focused on safety report DT pipelines that ingest worker/machine locations, equipment states, temporary-works conditions and environmental readings, then infer hazardous proximities, unstable configurations or deteriorating conditions before incidents propagate. The value lies in both situational awareness, visualising evolving hazards in a 4D context and the automated triggers that escalate when thresholds are crossed (for example, excessive worker-plant proximity or scaffold vibration anomalies). Luo et al. [2] synthesise this stream and characterise five recurring functions: real-time monitoring, early warning, analysis and prediction, optimisation of safety decisions, and safety management visualisation, arguing that the ‘decision-coupling’ pieces (rules/optimisation) are where impact concentrates. Allied work shows similar architectures improving responsiveness and reducing unsafe exposure through streaming analytics [13] (Table 2).

Risk-Based maintenance planning. Alongside incident prevention, DTs are widely used for predictive maintenance and risk-based inspection of critical plant and temporary works. By learning patterns in time-series (loads, vibrations, temperatures, oil metallic content, crane duty cycles), twins anticipate failure and propose inspection or replacement windows that minimise downtime exposure during

Table 2. Literature on DT in construction risk management.

Applications	References
Real-time Monitoring	[2,24, 48,49]
Risk-Based Maintenance	[16,24, 37,48, 50–52]
Enhanced Decision Making	[2,12, 16,23, 27,28,31]
Project Lifecycle Management	[30,33, 51,53,54]

risky phases of construction [16]. Digital twins' unparalleled use in sustainability and vulnerability assessments, which could facilitate the development of the next generation of risk-based inspection and maintenance frameworks [24]. By using data analysis digital twin predicts maintenance needs and optimises resource allocation, thereby mitigating the risk in construction projects [37]. A 2024 systematic review of predictive maintenance with DTs emphasises the role of supervised learning for accurate remaining-useful-life estimation and notes the spill-over of proven methods from other infrastructure/industrial domains into construction equipment fleets and temporary works [50]. More domain-specific reviews and methods papers describe how DT-enabled reduces unplanned outages and supports risk-based maintenance planning by converting condition indicators into probability-of-failure and consequence-of-failure metrics that can be optimised against programme constraints [51,52]. Operations-and-maintenance risk, although post-construction, feeds back into construction choices when projects adopt whole-life governance. Here, DTs support fault detection and diagnostics, bridging into commissioning and early operations with the same sensor and model backbone. Recent overviews report gains in fault diagnosis speed, energy risk mitigation and labour productivity by maintaining a continuously updated twin of building systems; this reduces warranty-period disputes and helps teams justify commissioning scope and contingency during construction [48,52]. When projects are procured under long-term performance regimes, these O&M risk reductions are a direct construction-phase benefit because they change design and installation risk appetites and reduce handover uncertainty.

Enhanced decision-making. Throughout the project lifetime, digital twins offer data-driven insights to facilitate well-informed decision-making. Quicker reactions to new problems are made possible by real-time data analysis, which lowers project delays and cost overruns [27,28]. Stakeholders can select the most effective and sustainable methods by using the ability to model various construction scenarios and forecast results. To accomplish better building management, DTs employ sensors and advanced analytics to provide actionable insights [2,23]. Lu et al. [31] noted that the current digital twin application in construction risk management includes enhancing safety through risk factor analysis. DTs that keep the virtual and physical 'in step,' so planners can run alternative sequences, crew allocations, and access strategies, and immediately see conflicts, delay risks and cost ripple effects before committing to the site [12]. Crucially, these DTs are not just visualisations; they embed rules and multi-criteria logic so that schedule, cost, safety and community impacts are weighed transparently when choosing a mitigation. Complementary research on AI-enabled risk management shows DTs acting as the substrate for simulating multiple site conditions in real time, letting teams compare risk scenarios and select the least-harm option with evidence [16]. By closing the loop from sensing → inference → 'what-if' → action, these applications reduce decision latency, often a hidden driver of compounding risk on urban sites.

Project lifecycle management. Throughout the whole construction project lifespan, from design and planning to maintenance and eventual decommissioning, digital twins enable increased efficiency, thereby reducing risk in projects [53]. Jiménez Rios et al. [51] addressed how digital twins enable occupational efficiency by making it easier to maintain and monitor structures across their lifetimes. Project managers can simulate and forecast how a building will behave in different scenarios by generating a virtual model of the actual structure. This enables proactive maintenance and long-term sustainability [54]. Progress and quality assurance also benefit from DT coupling. When photogrammetry/LiDAR updates, machine logs and submittal/RFI metadata are fused in the twin, deviations from plan out-of-tolerance elements, late deliveries, or quality non-conformances are surfaced earlier and linked to specific tasks, subcontractors and temporary-works states. Opoku et al. [33] point to logistics and monitoring as established DT application areas, with the research frontier now pulling those signals into risk-aware decision models rather than treating them as isolated progress checks. Lu et al. [30] confirm this trajectory in their 2018–2024 systematic review of 842 DT papers across buildings, landscapes and urban environments, noting a clear trend from isolated facility or component twins towards integrated, multi-source decision support spanning construction and operations.

3.1.3. RQ3: What framework integrates DTS into decision-making processes to enhance building resilience?

A consistent theme in recent literature is that resilience gains from Digital Twins (DTs) do not come from monitoring alone but from twins that formalise a sense–analyse–decide–act loop. In these decision-centred designs, the twin ingests live data, aligns those data with the building’s information model, propagates uncertainty through risk models, and then surfaces auditable choices for action. Three frameworks make this integration explicit: Cognitive Digital Twins (CDTs, including the building-focused COGNIBUILD approach), whole-life-cycle DT–BIM decision frameworks, and Risk-Informed Digital Twins (RDTs). Together, they move practice beyond descriptive dashboards towards evidence-based responses that maintain service and safety under stress.

Cognitive digital twin framework. The COGNIBUILD technique is based on the generation of DTS from information modelling (BIM), connecting three-dimensional objects to operation and maintenance data. It adds perception, memory, learning, and reasoning to a conventional twin so that the model itself can recognise disruptions and recommend, or trigger, responses. In a widely cited conceptualisation, Eirinakis et al. [13] describe a CDT that detects anomalies, retrieves relevant history, reasons about plausible causes, proposes and evaluates alternative courses of action, and learns from outcomes, all with the express aim of improving resilience to disturbances. This ‘noticing and acting’ capability compresses the time between weak signals and mitigation and reframes the twin as a decision entity rather than a passive visualisation. The CDT idea is not confined to manufacturing: building-scale implementations have been demonstrated by populating the twin with construction records, facilities data and building automation streams so that the cognitive layer can infer what is going wrong and why in real time. Studies jointly establish the CDT integration dimension (cognition layered over live telemetry and asset semantics) and the resilience mechanism (event recognition and adaptive response across the building lifecycle). Through input analysis, the model learns from its data from ticketing, BMS systems, and AI algorithms that process both expected and unexpected occurrences [11,28,30]. By enabling a system to recognise and manage events that could disrupt the construction process and to absorb and mitigate the resulting repercussions, the CDT can be used to support the resilience of construction processes [13]. Within this CDT family, COGNIBUILD offers a concrete, building-oriented technique that ties BIM objects to operation-and-maintenance data, ticketing logs and BMS/BAS streams, and then uses learning pipelines to anticipate issues and prioritise recovery actions. The framework’s distinctive contribution is to make the BIM model the substrate for decision logic: components and systems in the 3D model are bound to their histories, alarms and work orders, so recommendations are both explainable and actionable. As a result, cognition is operationalised at the building scale in a way that directly supports resilience, because the twin can connect an emerging anomaly to a specific asset, simulate alternative responses, and issue an instruction or recommendation quickly enough to prevent service degradation or safety incidents. El-Mokhtari et al. [15] complex systems with numerous interconnected subsystems and components that necessitate interactions between several lifespan phases are the focus of CDTs. Although its implementation is more difficult in terms of technological readiness, risk level, economic and time cost, etc., it can offer more sophisticated cognitive capabilities (Table 3).

Whole-life-cycle framework. Shen et al. noted that Digital twins (DT) and Building Information Modelling (BIM) technologies can be combined to help solve these issues and enable the integrated depiction of important factors to aid in decision-making throughout a building project’s lifecycle. Here, the breakthrough is not the cognitive layer but information governance across phases. Shen et al. identify the decision variables that most strongly determine outcomes such as net-zero performance and resilience; they map those variables to IFC entities, properties and relations; and they design a framework that ingests DT telemetry during operation to close the decision loop [30,31]. The key move is to

Table 3. Digital twins framework integration.

Framework	References
Cognitive Digital Twin Framework	[11,13, 15,28,30]
Whole-Life-Cycle Framework	[30, 31,50]
Risk-Informed Digital Twin	[16,21, 36,41]

treat decision variables as first-class objects in the information model. Because the same variables are represented consistently from design through construction and operation, choices made early can be re-examined and adapted later with live evidence. This cross-phase alignment is material for resilience: interventions affecting envelope robustness, passive survivability, comfort, safety and business continuity can be tested ex-ante, monitored in service, and then recalibrated as conditions change without losing traceability [50].

Risk-informed digital twin. The risk-informed digital twin integrates the framework of sustainable and resilient engineering (SRBE) into the decision-making process, and it enhances building resilience by addressing risks and facilitating comprehensive lifecycle analysis through stakeholder engagement [36]. RDT is made up of multiple modules (such as Uncertainty Quantification and Machine Learning, Health Monitoring, Risk Analysis, Decision Making under Uncertainty, and Optimal Control) and integrates the five stages of DT, including simulation, intelligent, and semi-autonomous DT [41]. Alibrandi et al. [16] formalises an RDT architecture with modules for uncertainty quantification and machine learning, structural/health monitoring, risk analysis, decision-making under uncertainty, and optimal control, all nested within a Sustainable and Resilient-Based Engineering (SRBE) framework. Rather than reporting deterministic states, an RDT maintains distributions over hazards and responses, ranks interventions by expected benefit under constraints, and implements optimal control policies when appropriate. Bia et al. [21] extends the idea to a Risk-Informed Digital Building Twin, emphasising multi-stakeholder and multi-criteria decision-making over the building lifecycle. The distinctive advance here is the quantitative backbone: uncertainty is propagated explicitly through models so that resilience choices, retrofit options, operational strategies, recovery plans are selected with transparent confidence and trade-offs.

These three families differ in integration dimension, risk-coverage scope and implementation burden, which explains why they are complementary rather than competing. CDTs integrate cognition with live operational and ticketing data to perceive and respond to disruptions as they unfold; they excel where continuity and rapid incident response determine resilience, such as critical services in hospitals or live phases of complex refurbishments. Whole-life frameworks integrate decision variables within BIM/IFC semantics so that design-time choices remain testable and traceable in operation; they excel where resilience depends on cross-phase coherence, for example, when evaluating adaptive envelopes, passive survivability under heat waves, or long-horizon maintenance strategies. RDTs integrate risk calculus so that decisions are explicitly uncertainty-aware and can be optimised; they excel where hazards are deep and multifactorial seismic, climatic, or cascading operational failures and where intervention timing and sequencing matter. The trade-offs are equally clear: CDTs and RDTs demand heavier analytics and data-engineering capabilities, while whole-life frameworks require stronger information-modelling governance and organisational alignment around open standards.

Positioned against those distinctions, a practical selection rule emerges. A CDT is preferable when the primary resilience objective is rapid situation awareness and event-driven response in live operations, because cognition compresses detection, diagnosis and action into a single loop. A whole-life DT-BIM framework is preferable when governance and traceability across phases are decisive, because representing decision variables explicitly in IFC makes choices portable and auditable from design to operation. An RDT is preferable when decisions must be compared rigorously under uncertainty and where the optimal timing of controls needs to be computed rather than judged heuristically. In many real projects, a hybrid is warranted: for example, deploying a CDT to manage operational incidents inside a whole-life BIM-DT stack, while RDT modules rank retrofit or operational scenarios under climate and market uncertainty. This hybridisation is increasingly reflected in roadmaps for synchronised construction and operations that treat resilience, alongside efficiency and sustainability, as a core decision objective rather than a side-effect of monitoring

3.2. Proposed framework: a digital twin-enabled decision support system (DT-DSS) for urban-renewal risk governance

The study proposes a Digital Twin-Enabled Decision Support System (DT-DSS) that treats the twin as a decision infrastructure rather than a monitoring dashboard. The framework formalises a closed

loopsense → analyse → decide → act → learn so live site/asset signals are converted into auditable choices fast enough to change outcomes on dense, disruption-prone urban renewal sites. This design directly answers recent reviews and roadmaps that call for DTs to move beyond visualisation towards explicit decision coupling and virtual–physical synchronisation during planning and execution [2,7,30].

At its core, the DT–DSS brings heterogeneous data into one decision pathway. Telemetry from safety wearables and equipment, vibration and geotechnical sensors, dust/noise and microclimate monitors, schedule and cost systems, and stakeholder-engagement records is ingested continuously. Each observable is engineered onto a common scale and tied to a concrete decision variable in the model (for example, ‘probability of hazardous proximity,’ ‘posterior risk of waterlogging at trench A,’ ‘grievance momentum before demolition’). Instead of remaining as a list of indicators, these variables are embedded in Bayesian network structures that propagate interdependencies so a change in rainfall and drainage capacity updates the probability of local flooding; a cluster of near-misses updates incident risk for the current shift; and a surge in unresolved complaints raises the likelihood of protest and delay. By updating posteriors with new evidence from the twin, the BN layer provides a live, uncertainty-aware risk picture that can answer ‘what-if?’ questions before action [21–24].

Decisions are then tested and ranked inside the twin rather than on paper. The DT–DSS runs scenario simulations to examine practical alternatives for re-sequencing a demolition, adding temporary drainage, shifting work windows during heat or dust peaks, or inserting extra stakeholder sessions and measures how each scenario shifts the BN-derived risk profile. Options are selected using a transparent multi-criteria decision analysis stack so that time, cost, safety exposure, environmental intrusion and community impact are weighed explicitly; the chosen action is the one with the best overall trade-off under current uncertainty. This closes the loop from streaming data to an evidence-based intervention that can be executed and audited [50,52].

Governance and traceability are built in. Every recommended action is bound to a threshold and a role that is authorised to approve, what evidence was used, and what rule or optimisation produced the recommendation. Decisions are recorded with full provenance: inputs → inference → scenario comparison → authorisation → outcome. To make these records portable across the supply chain, the framework aligns semantics to Industry Foundation Classes (IFC) so that decision variables are first-class objects attached to the 3D/4D model; for low-latency telemetry, we use a lightweight MQTT publish/subscribe layer. Using these open standards reduces vendor lock-in and makes decision flows inspectable across design, construction and operation [55,56].

The framework is intentionally compatible with the three decision-centred strands in the literature. From Cognitive Digital Twins (CDTs), it borrows the idea that a twin should recognise disturbances and propose or trigger mitigation, using memory, perception and reasoning layered on live telemetry; building-scale exemplars such as COGNIBUILD show how BIM objects can be tied to BMS/ticketing data so the twin learns from both expected and unexpected events [51,52,55]. From whole-life DT–BIM decision frameworks, it adopts the governance move of mapping decision variables to IFC so choices made at design remain traceable and updateable during construction and operation Shen et al. From Risk-Informed Digital Twins (RDTs), it inherits the quantitative backbone uncertainty quantification, risk analysis and decision-under-uncertainty modules so that resilience choices are not merely recommended but optimised and defensible [7]. The novelty here is the way these elements are combined inside a single, auditable pathway tailored to the multi-domain risks of urban renewal.

An implementation sketch helps to see how this works in practice. Telemetry streams into an MQTT broker and is persisted in a time-series store; batch feeds (permits, traffic, and costs) are ingested on schedule. A synchronised twin keeps the 3D/4D model ‘in step’ with the field, while analytics services host BN inference, anomaly detection, and the MCDA engine. Decision services maintain the rulebook of thresholds and escalations, a sandbox for scenario runs, and the audit trail. Because all entities and decision variables are IFC-addressable, recommendations appear in the right model context for site teams to execute. This matches the synchronised construction management ambition, reducing ‘decision latency’ by closing the loop from sensing to action [12].

Finally, the study states upfront how the framework will be judged in pilots: reductions in time-to-decision, avoided incidents and cost/schedule variance, prevented environmental exceedances, and

improvements in stakeholder satisfaction, alongside the share of decisions with complete provenance. These are the decision-centred KPIs contemporary DT roadmaps increasingly advocate and that reviewers asked us to foreground [12].

3.3. Framework overview

This section presents a high-level overview of the proposed DT–DSS framework, clarifying its architecture, key modules, workflow, and governance features to guide practitioners and researchers alike (Figure 6).

3.4. Architecture and key modules

Here, the DT–DSS framework is structured into four interconnected modules: (1) Data Ingestion & Synchronisation, (2) Risk Modelling & Analytics, (3) Decision Engine & Scenario Testing, and (4) Governance, Traceability & Learning.

- In the Data Ingestion module, heterogeneous data streams from IoT sensors, mobile devices, legacy systems, stakeholder engagement platforms, and project-control systems are unified through a light-weight middleware (e.g. MQTT publish/subscribe) and aligned via a semantic schema (e.g. IFC-tagged decision variables). This real-time synchronisation ensures the physical twin and digital twin remain tightly coupled.
- The Risk Modelling & Analytics module embeds Bayesian network structures, probabilistic reasoning and ‘what-if’ simulation engines. Here live indicators (e.g. Vibration → structural degradation

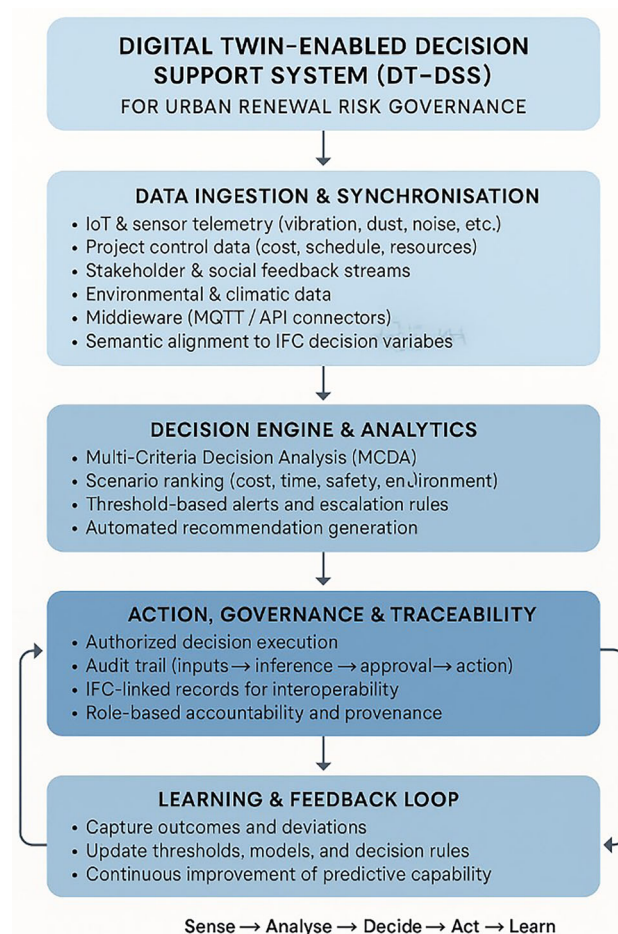


Figure 6. DT-DSS framework overview for urban renewal risk governance.

probability, Grievance → stakeholder disruption probability) propagate through inter-linked risk paths, enabling continuous updating of risk exposure and decision-ready metrics.

- In the Decision Engine & Scenario Testing module, alternative strategies (such as work-sequencing changes, temporary drainage insertion, stakeholder meeting protocols) are run through multi-criteria decision-analysis (MCDA) logic that weighs cost, schedule, safety, environment and community impact. The highest-ranked option is surfaced with transparent logic.
- Finally, the Governance, Traceability & Learning module records full provenance inputs, inference paths, scenario comparison, decision authorisation and outcome capture enabling auditability, post-event review and continuous learning. A back-end knowledge base updates thresholds, rules and scenario portfolios based on field experience.

Workflow: Sense → Analyse → Decide → Act → Learn

The framework's workflow is intentionally designed as a closed-loop:

- **Sense:** Real-time telemetry and project-control data flow into the twin.
- **Analyse:** Risk modelling updates posterior probabilities, scenario engines run 'what-if' tests.
- **Decide:** Decision engine selects optimal intervention path, logging authorisation and rationale.
- **Act:** Site teams execute the selected intervention; the system monitors execution and any emergent deviation.
- **Learn:** Outcome data is fed back into the twin, updating models, refining thresholds and improving decision logic for future cycles.

3.5. Governance and standards

To ensure practical operability and cross-stakeholder interoperability, the DT-DSS framework emphasises open standards. Decision-variables and model entities are aligned with Industry Foundation Classes (IFC) semantics; data transport utilises lightweight MQTT layers to avoid vendor-lock-in and enable broad integration. Governance features include role-based authorisation (who approves what), threshold-based escalation rules, and full audit trails. This alignment supports the twin's role not merely as a monitoring tool but as a **decision infrastructure** within urban-renewal governance systems. Research emphasises the need for digital twin frameworks to move from visualisation towards explicit decision-coupling and virtual-physical synchronisation [2,7,30].

3.6. Contextual compatibility and novelty

The proposed DT-DSS framework draws on three established strands from the literature: Cognitive Digital Twins (CDTs) with learning and reasoning layers; whole-life DT-BIM frameworks that preserve traceability across design, construction and operation; and Risk-Informed Digital Twins (RDTs) with explicit uncertainty quantification and optimisation logic. CDTs emphasise rapid response, whole-life frameworks emphasise governance across phases, and RDTs emphasise robust decision-under-uncertainty modules. Moreover, the novelty in this framework lies in **combining** these elements into a tailored system for urban-renewal risks (social, financial, environmental, and managerial) and embedding full decision-logic not just monitoring in the twin.

3.7. Implementation sketch and key performance indicators (KPIs)

A typical deployment might include:

- A time-series database ingesting telemetry stream (sensors, engagement logs, cost/control systems) via MQTT.
- A synchronised 3D/4D model (BIM) kept current via periodic LiDAR/photogrammetry updates.
- An analytics layer executing Bayesian inference and scenario engines.
- A decision interface presenting ranked options, authorisation workflow and execution triggers.

- KPIs for pilot evaluation: *time-to-decision, number of avoided incidents, schedule/cost variance reduction, number of environmental threshold exceedances prevented, stakeholder satisfaction improvement, percentage of decisions with full provenance*. These align with contemporary DT roadmaps calling for decision-centred metrics [12].

3.8. Risk quantification and decision logic

This subsection formalises how the proposed digital-twin decision support system (DT-DSS) converts live signals into auditable actions. We adopt a staged pipeline that begins with indicator engineering and normalisation, proceeds through probabilistic risk propagation and scenario simulation, ranks interventions using multi-criteria decision analysis (MCDA), and binds the outputs to pre-agreed triggers, roles and audit trails. Conceptually, this aligns with ISO-style risk processes and project-management practice, but moves beyond qualitative heat-maps by introducing explicit uncertainty modelling and optimisation so that decisions are evidence-based rather than dashboard-based (PMI's quantitative risk principles; critiques of probability–impact matrices) [19,45,46].

3.8.1. Indicator engineering and normalisation

Heterogeneous DT data worker/plant proximity breaches, vibration and dust peaks, schedule variance (SPI/CPI), cash-flow buffers, grievance volumes, relocation-milestone adherence, drainage capacity and rainfall, heat/noise exposure are first mapped to a common [0, 1] scale to enable aggregation and comparison across domains. Where teams already use a probability–impact (P–I) matrix, we treat that as the entry to quantification: qualitative ratings are translated to numeric likelihoods and impacts with documented thresholds, and we preserve the trace from raw readings → transformed indicators → resulting risk scores in the log. This step responds to well-known limitations of P–I matrices (scale compression, boundary effects) by making the mappings explicit and by preparing indicators for probabilistic updating downstream (PMBOK/qualitative→quantitative transitions; quantitative critiques and improvements) [41,45,46].

3.8.2. Probabilistic risk propagation (Bayesian networks)

Interdependencies among risks are captured with Bayesian Networks (BNs) that represent causal links such as equipment degradation → incident likelihood, rainfall × drainage → waterlogging around excavations, or grievance momentum → protest risk. This allows continuous learning as telemetry streams in, and supports ‘what-if’ queries by intervening on nodes. Recent construction safety work and structural/asset management studies show BN variants (including fuzzy BNs) improving risk inference and decision support under uncertainty [44,45, 47,52].

3.8.3. Dynamic inference, value of information, and optimal policies

For deteriorating systems and time-sequenced decisions, we use dynamic BNs and decision processes to compute when to inspect, repair, or re-sequence work. This enables formal value-of-information (VoI) analysis whether an extra sensor, inspection, or survey changes the decision enough to justify its cost and optimal control under uncertainty. Recent SHM research quantifies VoI with dynamic BNs, and reliability/maintenance studies combine dynamic BNs with Markov/MDP policies to select actions that minimise expected risk and cost over the horizon. Data-quality effects (e.g. biased sensors, drift) are treated explicitly so their impact on decisions is visible [47,50,51].

3.8.4. Scenario simulation and synchronised execution

Alternative interventions demolition sequences, temporary drainage layouts, staggered work windows during heat or dust exceedances and compensation-engagement calendars are tested virtually before commitment. We combine agent-based and system-dynamics styles where useful: ABM to represent interacting crews, plant and bystanders; SD to capture accumulations (delays, inventory, grievances) and feedback. The ‘synchronised construction management’ roadmap frames this as keeping the virtual and physical ‘in step,’ so scenario winners are executed quickly and re-evaluated as new data arrive [16,53,55].

3.8.5. Multi-criteria decision analysis (MCDA) for option ranking

To choose among feasible interventions, we apply a transparent MCDA stack. We elicit stakeholder priorities (e.g. time, cost, safety exposure, environmental intrusion, community satisfaction) via AHP/BWM to obtain a weight vector www , with consistency checks; we then rank options using TOPSIS (or PROMETHEE/ELECTRE where outranking is preferable). In TOPSIS, each option's closeness C^* to the ideal is $C^* = D^- / (D^+ + D^-)$, where D^+ and D^- are distances to the positive/negative ideal points in the weighted normalised space. Construction risk studies have long combined AHP with TOPSIS, and recent work uses BWM–TOPSIS hybrids for risk portfolios; ASCE contributions show PROMETHEE/ELECTRE integration for engineering trade-offs [18,24, 45,50].

3.8.6. Decision rules, triggers, and accountability

Probabilistic and MCDA outputs are bound to pre-agreed thresholds and roles. For example: if P (waterlogging hot-spot) > 0.4 and noise intrusion is low, re-sequence haul operations and activate temporary drainage; if proximity alerts exceed n within an hour, halt and re-brief; if the grievance index rises above a set level before demolition, delay and convene mediation. Thresholds, evidence, recommended action and the authorised decision-maker are logged for audit. This makes qualitative governance artefacts (risk registers, thresholds, tolerances) operational in the twin and aligns with recognised project-risk practice while overcoming the static nature of traditional heat-maps [20,52,53].

3.8.7. Learning loop and model governance

After each decision, outcomes (incidents avoided, delay avoided, complaints resolved, cost variance) feed back into BN parameter learning and weight updates in MCDA. To support maintainability and vendor-neutrality, we implement the twin on open standards: IFC (ISO 16739-1) carries asset semantics and relationships across design–construction–operations; MQTT (ISO/IEC 20922) provides a lightweight, reliable publish/subscribe transport for live telemetry. Both standards are stable and widely adopted, and their use simplifies provenance, access control, and cross-platform interoperability in construction settings [55,57,58].

3.8.8. Evaluation metrics and reporting

We evaluate the DT–DSS on decision-centric KPIs: time-to-decision, number of leading-indicator alerts acted upon, incidents and near-misses avoided, schedule variance reduction, cost of change avoided, environmental exceedances prevented, and stakeholder-satisfaction deltas. For construction-phase synchronisation, we also report ‘decision latency’ (sensing→action elapsed time) and the share of decisions with complete provenance (inputs→inference→action→authoriser). These metrics reflect the thrust of synchronised-management road mapping and emerging ‘risk-informed twin’ prototypes that compute and visualise risk in real time [16,30].

3.9. Discussion

This review set out to understand how Digital Twins (DTs) are currently used for construction risk management, what classes of risk matter most in urban renewal, and what a decision-centred DT architecture needs in order to improve resilience. Across the literature, the direction of travel is clear: DTs are moving from descriptive mirrors of site conditions towards closed-loop, decision-oriented systems that couple sensing, simulation and explicit rules so that risk is anticipated and acted on in time. Contemporary syntheses position this shift explicitly; for example, Luo et al. [2] identify real-time monitoring and early warning as mature functions but argue that impact concentrates when these signals are bound to decision rules and optimisation rather than ending on dashboards, while Jiang et al. [16] call for ‘synchronised construction management’ that keeps the virtual and physical in step from sensing → inference → scenario testing → action. Our findings align with those trajectories and, taken together with broader reviews of DT practice in construction, support reframing DTs as decision infrastructure rather than visualisation tools.

A first implication concerns where today's DTs already reduce risk and where gaps remain. The most mature applications sit in safety monitoring/early warning and in predictive maintenance/

inspection of critical plant and temporary works, where streaming analytics detect hazardous proximities or degrading states before incidents occur; these uses are well documented and increasingly leverage machine-learning estimators for remaining-useful-life to cut downtime exposure. Yet even in this advanced stream, authors emphasise that measurable gains appear when outputs are tied to transparent decision pathways, thresholds, escalation and optimisation rather than treated as situational awareness alone [2,31,50]. Planning/execution support is the next area of consolidation: ‘synchronised’ DTs are used to test sequences, access strategies and crew allocations, with chosen mitigations pushed back to site in near real-time to shorten decision latency, a hidden driver of compounding risk on dense urban sites [16]. By contrast, multi-domain renewal risks, especially social and environmental risks, remain under-modelled inside many twins even though they frequently trigger delays and reputational harm; here the literature points to the need to integrate grievance/engagement signals, dust/noise/heat exposure and waterlogging susceptibility into the same decision loop used for safety and schedule [32].

Second, the review clarifies what is novel in a DT-enabled decision support system (DT-DSS) for urban renewal. The novelty is not a new sensor or a prettier model; it is the data-to-decision pathway: a) engineering comparable indicators across safety, financial, social and environmental domains; b) propagating uncertainty via Bayesian Networks so interdependent risks update as evidence arrives; c) running scenario simulations (e.g. re-sequencing, temporary drainage, work-window shifts) inside the twin; and d) selecting actions with multi-criteria decision analysis so time, cost, safety, environment and community trade-offs are explicit and auditable. Each step is grounded in methods with growing uptake in the AEC context BNs for accident causation and risk inference; dynamic BNs and decision processes for inspection/repair timing; and AHP/TOPSIS-style MCDA for ranking interventions so the contribution lies in linking them coherently within the DT rather than advocating any one technique in isolation [26,31, 32,37,48]. Third, the comparison with decision-centric frameworks helps position the contribution with respect to integration breadth and risk scope precisely as reviewers requested. Cognitive Digital Twins (CDTs) show how adding perception, memory, learning and reasoning to a twin enables event recognition and rapid, event-level response; this is valuable wherever continuity and incident recovery dominate resilience [13,53]. Whole-life DT-BIM frameworks make variable-level governance the centre of gravity by representing decision variables in IFC and updating them with DT telemetry across design, construction and operations; this strengthens resilience where cross-phase coherence matters most [17]. Risk-Informed Digital Twins (RDTs) provide an uncertainty-level backbone by embedding modules for uncertainty quantification, risk analysis and decision-making under uncertainty so choices can be optimised and defended [16,37]. Our DT-DSS adopts a hybrid stance: cognitive elements for live phases (fast sense-decide-act), IFC-aligned variables for lifecycle traceability, and risk-informed modules where deep uncertainty dominates. This hybridisation explains both the integration dimension (sensing→analytics→decisions→governance) and the risk coverage (technical, social and environmental) that reviewers asked us to make explicit.

Fourth, the practical implications for clients, contractors and city authorities are concrete. For adopters, the fastest path to value is to start with a minimal but consequential indicator set (e.g. proximity/near-misses, schedule variance, dust/noise peaks, grievance velocity) and to bind each indicator to a rule and a role; then add BN inference and a small portfolio of ‘what-if’ simulations that test re-sequencing and mitigation before action; and finally introduce MCDA so that the inevitable trade-offs become transparent. For information governance, interoperability matters: aligning semantics to IFC (ISO 16739-1) and using MQTT (ISO/IEC 20922) for live telemetry reduces vendor lock-in and makes decision provenance auditable across teams and phases practical requirements echoed by whole-life DT-BIM work [17,58,59]. For performance management, decision-centred KPIs such as time-to-decision, near-misses/incidents avoided, schedule variance reduction, environmental exceedances prevented and stakeholder-satisfaction deltas better reflect DT value than model fidelity alone.

Fifth, the analysis surfaces challenges and how to mitigate them. Interoperability and data fragmentation continue to slow the flow from sensing to decision; open standards and published APIs are the primary countermeasures [17,50]. Data quality, latency and model drift can erode trust in alerts; quality gates, redundancy and scheduled recalibration of BN parameters and MCDA weights are needed. Social-risk modelling is thin in many implementations even though compensation, relocation and

participation dynamics can determine programme outcomes; integrating grievance/engagement data and adopting decision rules that require consultation before disruptive works are practical steps. Finally, governance and privacy concerns around location and safety telemetry must be addressed with role-based access and transparent audit trails; these issues are well-known in urban DT deployments and cannot be bolted on at the end [19].

While the review synthesises and systematises a fast-moving field, many primary studies are proof-of-concepts or partial pilots; causal claims about outcomes remain sparse outside safety and maintenance. Our method emphasises conceptual integration and method feasibility (BNs, MCDA, scenario simulation) and triangulates against authoritative reviews and roadmaps; nevertheless, field validation is still necessary to quantify effect sizes in real projects. Following Jiang et al. [7], the study outlines a staged evaluation in two urban-renewal pilots that measure decision latency, avoided incidents/costs, environmental exceedances prevented and stakeholder outcomes precisely the decision-centred KPIs that DTs should improve if the coupling is real.

Finally, the review motivates a research agenda. First, expand decision-centred DT studies beyond safety into multi-domain renewal risk, especially by joining environmental exposure (dust/noise/heat, waterlogging) and social indicators (complaints, compensation progress) to the same BN/MCDA loop now used for safety and schedule [44]. Second, prioritise comparative trials that benchmark closed-loop DT–DSS against business-as-usual monitoring on matched sites; without counterfactuals, DT value is hard to attribute. Third, publish open protocols BN structures, decision rules, MCDA criteria and weights so that other teams can reproduce and stress-test results, accelerating learning across contexts. Fourth, deepen integration with risk-informed modules where uncertainty is high (e.g. climate extremes, seismic retrofit), leveraging the RDT literature to make optimisation and uncertainty propagation standard parts of practice [16]. These steps align the field with what recent syntheses already signal: the frontier is not more sensing but better decisions, faster, under uncertainty, with traceable trade-offs.

3.10. Recommendations and conclusions

A revolutionary approach to managing complex risks in urban renewal construction is provided by the incorporation of Digital Twins (DTs) into decision support systems. DTs facilitate proactive risk identification and mitigation in the social, financial, environmental, and management domains by utilising real-time monitoring, predictive analytics, and frameworks such as Cognitive and Risk-Informed Digital Twins. Through lifecycle management, scenario simulations, and data-driven insights, these technologies improve resilience, encouraging stakeholder collaboration and enhancing project results. However, obstacles like exorbitant prices, barriers to interoperability, and disjointed standards prevent broad adoption. Governments, businesses, and academia must work together to create standardised protocols and scalable solutions to overcome these. Pilot projects, workforce development, and investments in digital infrastructure can lower financial and technical barriers while proving useful. Prioritising inclusive planning and community involvement is equally crucial for addressing socioeconomic risks and guaranteeing fair results. To align urban renewal with sustainability objectives, future initiatives should concentrate on interoperable systems, standardised data practices, and adaptive strategies. Stakeholders can fully utilise DT-enabled systems to build resilient, future-ready urban environments by filling in these gaps.

3.10.1. Implications for theory

Theoretically, positioning the twin as decision infrastructure reframes DT research around three converging pillars. First, cognition: Cognitive Digital Twins (CDTs) show that perception, memory, learning and reasoning can be layered on a DT so the system recognises disturbances and proposes responses, compressing the interval from weak signal to mitigation. That pushes theory beyond state representation into event understanding and action selection. Second, lifecycle semantics: whole-life DT–BIM work demonstrates that when decision variables are represented in an IFC-based information model, choices made at design remain traceable and updateable during construction and operation, making resilience a property of the information architecture, not an afterthought. Third, formal risk

calculus: Risk-Informed Digital Twins (RDTs) embed uncertainty quantification, risk analysis and decision-under-uncertainty, ensuring interventions are ranked and timed with transparent trade-offs. Our results suggest that a mature theory of DTs in construction integrates these strands cognition, lifecycle semantics and risk calculus into one auditable pathway from evidence to action.

3.10.2. Implications for practice

For practitioners, the clearest path is phased. Start with a minimal but consequential indicator set that already exists on most sites: proximity/near-misses, schedule variance (SPI/CPI), dust/noise/heat peaks, and grievance velocity and bind each indicator to a rule and a responsible role. Add a Bayesian updating layer so interdependent risks (e.g. rainfall $\times$ drainage $\rightarrow$ waterlogging; unresolved complaints $\rightarrow$ protest risk) update as evidence arrives, and use the twin to run ‘what-if’ scenarios before committing to the site. Introduce a transparent multi-criteria ranking so time, cost, safety, environment and community impact are weighed explicitly. Under the hood, keep the stack standards-based use IFC so decisions and their rationales live with model objects, and MQTT for low-latency telemetry to reduce vendor lock-in and make audit trails portable across the supply chain. Evaluate the programme with decision-centred KPIs, not model fidelity: time-to-decision; near-misses/incidents avoided; schedule and cost variance reduced; environmental exceedances prevented; and stakeholder-satisfaction deltas. These steps operationalise the ‘decision-coupling’ gap identified in safety reviews and the synchronisation ideal in recent roadmaps, while aligning with widely adopted interoperability standards.

3.10.3. Limitations and future work

This review and framework synthesis rely largely on secondary evidence and method feasibility; many primary studies remain proof-of-concept or partial pilots. A priority is prospective validation through controlled pilots on urban-renewal projects, comparing closed-loop DT–DSS against business-as-usual monitoring and reporting effect sizes on decision-centred KPIs. Methodologically, the next frontier is fuller integration of socio-economic risk into the same loop that now handles safety, schedule and environment: grievance momentum, compensation progress, participation coverage and reputational signals should be engineered as first-class indicators with thresholds and escalation rules, then linked to scenario tests (e.g. re-sequencing demolition to accommodate additional engagement). Finally, connect asset- and site-scale twins to district- or city-scale twins so that decisions consider network effect traffic disruption, ambient air/noise baselines, heat-island dynamics and align with urban resilience objectives. Recent roadmaps explicitly call for validating synchronised DTs in real-world settings and for exploring synergies between DTs, AI and smart-city platforms; these are natural testbeds for the proposed DT–DSS.

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Authors’ contributions

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