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Digital Twin Implementation in Building Lifecycle for Sustainable Urban Development

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Abstract. Recent technological advances offer significant promise for enhancing architectural practice through the Digital Twin paradigm, which constructs a continuously updated virtual counterpart of physical assets to facilitate persistent, data-driven oversight, synthesis, and refinement. Conceived within the broader framework of sustainable development, Digital Twin endows decision-makers with the analytic leverage to boost energy performance, curtail greenhouse-gas outputs, and promote protracted asset durability via informed, asset-responsive management within a circular lifecycle. This study probes the prospective incorporation of Digital Twin technologies at each phase of the asset lifecycle, namely: strategic programming, realization, and enduring operation and stewardship. A qualitative methodology comprising a systematic literature synthesis and a portfolio of landmark international case studies involving Digital Twin in sizeable, sustainability-oriented architectural undertakings guides the inquiry. Outcomes reveal that systematic Digital Twin integration catalyses fundamental digital reform within the architectural field, strengthens data accountability across governance and technical boundaries, and underpins performance-oriented, environmentally conformed decision pathways. The research counsels a staged, phased dispersal of the technology, concentrating initial initiatives upon multi-unit housing and institutional assemblies in tropical climates, in furtherance of sustained, equitable urban advancement.

Keywords: Digital Twin, lifecycle building, sustainable architecture, building management, digital transformation.

1 Introduction

Digital transformation has irrevocably reshaped the design, construction, and operation processes of built environments. Among the most consequential innovations in this transformation is the Digital Twin (DT)—a living digital counterpart of a physical asset, continuously updated through real-time sensor data acquired over the entire lifecycle of that asset [1, 2]. Within the architecture and construction sectors the DT paradigm has matured beyond passive three-dimensional representations; it has become an autonomous decision-support apparatus that conducts continuous performance assessment, permits operational scenario testing, anticipates system failures, and informs

© The Author(s) 2025
L. Warlina and S. Luckyardi (eds.), *Proceedings of the 8th International Conference on Informatics, Engineering, Science & Technology (INCITEST 2025)*, Advances in Engineering Research 287,
https://doi.org/10.2991/978-94-6463-924-7_20

data-led strategic choices at scales ranging from individual buildings to entire campus districts [3, 4].

Framed within sustainable development objectives, the Digital Twin emerges as a force multiplier for energy optimization, carbon emission abatement, asset longevity, and systemic ecological robustness, all achieved through harmonised lifecycle governance [5, 6]. Additionally, DT is broadening the operational scope of designers, planners, and facility operators by equipping them to manage intricately coupled urban processes. This capability is especially significant within tropical regions and rapidly urbanising nations, where accelerating migration, compressing infrastructure timelines, and chronic resource scarcities require precision adaptive governance [7, 8].

Extensive investigations have recorded diverse utilizations of Digital Twin (DT) paradigms across civil engineering, advanced manufacturing, and smart city frameworks [9, 10]. Yet, emerging distinctive features of the technology indicate that the employment of DT within holistic building lifecycle management, particularly within architectural practice and sustainable territorial development, remains markedly underexplored from both theoretical and operational standpoints [11, 12]. Crucially, the confluence of DT, sustainable design methodologies, and socio-ecological tenets emerges as indispensable for the realization of built environments able to accommodate progressive climatic and social shifts.

Consequently, the present investigation seeks an evaluative appraisal of Digital Twin deployment across building lifecycle governance as an instrument of urban sustainable development. By assimilating contemporary scholarship, worldwide exemplars, and horizon-testing within the distinctive parameters of tropical architectural practice, the research advances a conceptual scaffold directed toward forthcoming initiatives situated within developing economies.

Through the constructive documentation of contemporary technological modalities, governing integration impediments, and regional contextual affordances, the paper aspires to consolidate the Digital Twin's status as an autonomous instrument rather than a mere technological excipient—positioning it as scalar evaluative, operational, and strategic artefact for the concurrent design, stewardship, and governance of resource-efficient, resilient, and sustainable settlements.

2 Literature Review

2.1 Concept and Architecture of Digital Twin

The Digital Twin (DT) paradigm constitutes a time-synchronized virtual embodiment of a tangible object, facilitating bidirectional, millisecond-scale exchanges via a synergy of Internet of Things (IoT) transducers, three-dimensional visualization, artificial intelligence, and empirical data scrutiny [1, 2]. A DT's structural scheme is predicated upon cyber-physical constructs that are woven into heterogeneous communication fabrics, bolstered by interoperability scaffolding and modular software fabrications [9]. To operationalize such a framework, stringent reference architectures—exemplified by makeTwin—are paramount; only then can Digital Twin (DT) assemblages manifest flexibility, elastic extendability, and cross-domain pertinence. This syntactic and architectural cerebral substrate effectively transverses all temporal segments of the architectural lifecycle, concurrently harvesting, curating, and interrogating datasets, thereby rendering the DT a predictive, inferential, and observative representation of a building's contingent performance response [3].

2.2 Role of DT in Building Lifecycle Management

The deployment of Digital Twin (DT) technology within Building Lifecycle Management (BLM) furnishes a cohesive framework that encompasses every phase of a building's life—from initial programming and design through construction to the continuous operation and eventual renewal of the asset [10, 11]. Within this context, the DT functions as a living repository, continuously assimilating and correlating real-time sensor metrics with critical performance indicators, including relative humidity, thermal gradients, occupancy density, energy flows, and structural safety margins. Recent findings advance this premise by illustrating a promising convergence of DT and blockchain architectures, thereby embedding immutable provenance and chronological certification of the recorded data over the entirety of the asset's duration [4]. Collectively, these characteristics afford analytics frameworks the stability and fidelity required for anticipatory maintenance programming and the enduring vitality of low-carbon, market-ready structural interventions [7].

2.3 DT for Sustainability in the Construction Industry

Digital Twin (DT) technology emerges as a decisive facilitator of sustainability advancement within the building industry by enabling performance simulation, design refinement, and judicious resource allocation. DT allows the quantification of a building's environmental footprint as soon as the schematic phase, thereby furnishing designers with information capable of curbing both embodied and operational carbon as well as diverting waste from landfill [6]. This potential is corroborated by empirical evidence from DT implementations in educational structures, where sustainability variables—namely thermal performance, energy balance, and pathways toward a net-zero energy result—are modeled concurrently and iteratively [5]. Further, urban applications of DT are being advanced in the context of metropolitan systems, the integration of feedback loops that solicit resident inputs on city services, thereby broadening the participatory horizon of urban design to incorporate the priorities of everyday users [8].

2.4 Implementation Challenges and Social Aspects

Despite offering extensive benefits, the implementation of DT still faces various technical and social challenges. The importance of developing interoperable reference architecture standards is emphasized to enable the integration of Digital Twin (DT) into complex and heterogeneous systems [3]. Development of DT must consider social sustainability, including data rights, algorithm transparency, and user involvement in the decision-making process [12]. Additionally, the management of large-scale data raises ethical, security, and privacy issues that, if neglected, can undermine the legitimacy of DT as a public technology.

2.5 Research Gaps and Tropical Architecture Context

Most current DT literature still focuses on developed countries and has not explicitly reviewed its application in tropical environments, which have different climate, social, and infrastructure characteristics. A recent study highlights the lack of Digital Twin (DT) research in resource-limited regions, where this technology has the potential to yield transformative impacts [1]. Further research is needed to explore how the integration of DT with passive design strategies and local construction can support climate resilience and resource efficiency in tropical areas.

The overall comparison of studies can be seen in Table 1.

Table 1. Comparison of Previous Studies on Digital Twin in Built Environment Context.

Researcher	Study Focus	Main Contribution	Application Context	Relevance to Tropical Architecture
[1]	Review of DT application in built environments	Identification of DT applications, challenges, and capabilities	Global	Emphasizes the importance of local context adaptation
[9]	Architecture and DT networks	Development of a DT framework in cyber-physical systems	Theoretical and technical	Provides a technical foundation for DT development
[11]	Integration of DT with Blockchain for lifecycle management	Concepts of data security and efficiency in the building lifecycle process	Construction industry	Potential efficiency for tropical housing projects
[6]	DT in sustainable construction industry	Emission reduction, energy efficiency, resource management	Building industry	Relevant for net-zero strategies in hot climates
[5]	DT for sustainability assessment in educational buildings	Real-time performance evaluation of buildings using DT	Educational buildings in Europe	Precedent study for schools in tropical regions
[3]	DT software platform	System architecture recommendations for large-scale implementation	Software industry	Potential for replication in smart city projects

Table 2 (Continued). Comparison of Previous Studies on Digital Twin in Built Environment Context.

Researcher	Study Focus	Main Contribution	Application Context	Relevance to Tropical Architecture
[12]	DT and social sustainability	Relationship between technology, data transparency, and social welfare	Global construction industry	Important for community participatory approaches
[4]	Provenance of DT data based on blockchain for predictive maintenance	Data validity and security mechanisms for building assets	Building facility management	Ensures data reliability in public buildings in humid climates
[7]	DT for extreme infrastructure	Vulnerability assessment and risk-based maintenance planning	Bridge infrastructure	Relevant for tropical regions prone to natural disasters
[10]	DT workflow for existing infrastructure	Development of DT workflows for aging construction	Civil infrastructure	Retrofit approach for existing tropical buildings
[2]	Trends and architecture of DT in construction	Comprehensive survey: applications, challenges, and system architecture	Global construction and architecture	Provides a trend map for adapting to tropical contexts
[8]	Smart city DT for citizen feedback	Integration of DT with public participation and smart governance	Urban (smart city)	Unlocks potential for participatory planning in tropical cities

3 Method

This research employs a descriptive qualitative approach, primarily utilizing literature review and selected case study analysis. The aim is to thoroughly examine the potential and challenges of implementing Digital Twin (DT) technology in building lifecycle management to support sustainable development, particularly in tropical urban areas.

The initial phase of the research involves a systematic literature review of journal articles, technical reports, and relevant academic publications from the past five years (2021–2025). The literature search is conducted through scientific databases such as ScienceDirect, SpringerLink, and MDPI using keywords including: digital twin, building lifecycle management, sustainable architecture, and urban development. The selected literature is categorized into three main groups: 1) Concepts and architecture of Digital Twin; 2) Applications of DT in construction and architecture; 3) Integration of DT with sustainability goals and implementation challenges.

Case study analysis is conducted to reinforce theoretical findings through comparative analysis of five international case studies that have implemented Digital Twin technology in large-scale sustainable urban or public building projects. The criteria for case study selection include: 1) Availability of technical documentation and performance evaluation results of the buildings; 2) Relevance of the context to sustainable architecture principles; 3) Potential for replication in tropical and developing regions.

Analysis involves reviewing: 1) Implementation strategies of DT; 2) The role of DT in energy efficiency and building lifecycle management; 3) Stakeholder engagement (architects, facility managers, users); 4) Technical and social challenges in implementation.

The results of the literature review and case studies are analyzed thematically to identify application patterns, common barriers, and opportunities for adapting DT technology in the tropical context. This synthesis is utilized to develop a conceptual framework for the implementation of Digital Twin that is relevant for sustainable architecture projects in resource-limited regions. The specific case studies analyzed are detailed in Table 2.

Table 2. Selection of Case Study Objects.

Project Name / Location	Digital Twin Focus	Impact / Advantages	Tropical Adaptation Potential
1. Nanyang Technological University (NTU), Singapore	Smart Campus with DT for energy management and predictive maintenance	Reduction in energy consumption by up to 31%; real-time monitoring of temperature, humidity, and occupancy	Highly relevant: humid tropical climate, institutional scale, and Southeast Asian context
2. City of Helsinki, Finland	3D City Model + DT for urban planning and carbon emissions evaluation	Spatial simulation of building thermal performance, transportation, and energy consumption	Can be adapted for tropical urban areas needing participatory and sustainable planning models
3. West Cambridge Digital Twin, University of Cambridge, UK	Monitoring research buildings and learning spaces; optimization of space and energy consumption	Reduction in operational costs & increased efficiency of space usage	Suitable for tropical education areas (schools, campuses)
4. Sejong Smart City, South Korea	New city based on DT for smart governance, mobility, and housing	Integration of data across the entire city infrastructure: buildings, transportation, utilities	Inspirational for the development of new tropical areas (e.g., IKN in Indonesia)
5. Edge Olympic Building, Amsterdam, Netherlands	Smart office building based on sensors and DT for lifecycle management	Automated management of lighting and ventilation → improved comfort & energy efficiency	Relevant for offices in tropical climates with high electricity consumption issues

4 Results and Discussion

4.1 Digital Twin as a Building Lifecycle Management Instrument

The results of the literature review and case studies indicate that the implementation of Digital Twin (DT) offers a significant leap in the management of building lifecycles. By integrating real-time data, digital modeling, and artificial intelligence, DT enables continuous monitoring of building conditions, predictive maintenance planning, and the optimization of energy usage—all within a single integrated system. DT no longer functions merely as a static visualization tool but has evolved into a performance-based decision-making platform.

Digital Twin (DT) technology possesses three primary capabilities in the context of built environments: (1) real-time monitoring of building conditions, (2) simulation to test building performance scenarios, and (3) optimization to support managerial decision-making. These capabilities have proven effective in case studies such as the Edge Olympic Building in Amsterdam and West Cambridge in the UK, where DT is utilized for the automatic regulation of lighting, ventilation, and HVAC systems [1]. These systems are classified as part of a reference architecture that supports interoperability among devices and subsystems, thereby positioning Digital Twin (DT) as the "digital brain" of buildings [3].

The energy savings attributed to Digital Twin technology is empirically grounded, not conjectural. Document that exemplary sustainable construction projects employing Digital Twin models attain energy savings of 15 to 30 percent, with proportional declines in greenhouse-gas emissions [6]. A complementary investigation examined educational facilities subjected to dynamic Digital Twin analyses, which assessed thermal performance, water use, and cross-ventilation strategies, yielding harmonized energy-efficiency indicators [5].

In tropical climates, where obligatory cooling loads remain persistently elevated, Digital Twin utility is accentuated. The Smart Campus of Nanyang Technological University, Singapore, serves as an illustrative case where perceptual models of air temperature, relative humidity, and occupant density trigger real-time calibrations of ventilation and lighting. Observed outcomes document simultaneous reductions in energy expenditures and enhancements in thermal comfort and occupant health, underscoring Digital Twin contributions to social sustainability [12].

The efficacy of Digital Twin models is further augmented when coupled with auxiliary technologies, notably blockchain, which safeguards data provenance and traceability through entire building lifecycles [11]. This enhanced transparency not only fortifies facility-management accountability but also instruments user engagement in governance, thereby elevating participatory design values in public and social-housing facilities, particularly in tropical jurisdictions.

Consequently, Digital Twin (DT) technology emerges as both a technological and strategic management lever, facilitating the design and operation of built environments characterized by adaptability, energy efficiency, and climate resilience. This is of particular relevance to developing nations experiencing rapid urbanization and confronting intricate infrastructure discontinuities. The conceptual framework is graphically represented in Fig. 1.

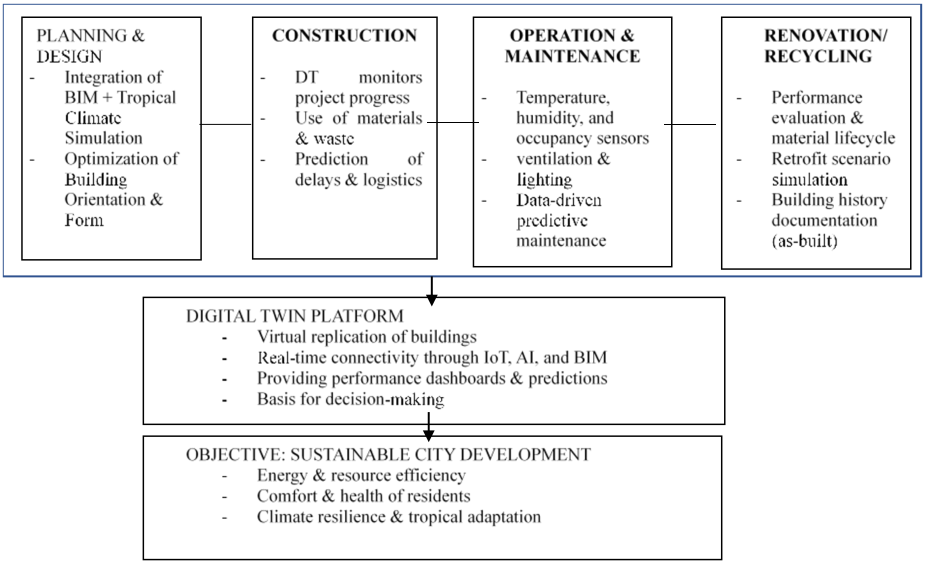

Fig. 1. Thought Flow of Building Life Cycle Management Instruments.

4.2 Transformation of the Roles of Architects and Facility Managers

The adoption of Digital Twin (DT) technology within built environments has catalyzed a restructuring of professional responsibilities, particularly for architects and facility managers. By creating accurate, real-time digital replicas of a building's physical phenomena, the architect's mandate has lengthened beyond the boundaries of design and construction and now necessitates continual oversight of building performance throughout the post-occupancy phase [1, 9]. Consequently, practitioners must cultivate a facility-level data literacy, permitting them to interrogate spatial performance metrics and to engineer building systems that adaptively recalibrate in response to fluctuating conditions. Simultaneously, facility managers are evolving from technical operatives to data-augmented strategists; expertise with advanced digital visualization environments and the nuanced interpretation of instantaneous performance metrics are now regarded as cardinal skills within a data-centric management paradigm [3]. It has also been argued that the observability and feedback loops enabled by DT frameworks enhance social sustainability by empowering management teams to deliver highly responsive interventions, thereby prioritizing occupant comfort and safety while aligning facility performance with collective social goals [12].

The ongoing digital transformation catalyzes the formulation of innovative curricula and professional development initiatives that encompass Building Information Modeling (BIM), the architectural underpinnings of digital twin (DT) systems, and the synergistic coordination with artificial intelligence [6]. Within emerging economies, these initiatives face heightened impediments resulting from fragmented digital infrastructure and limited workforce preparedness. Consequently, the adoption of a phased, context-sensitive strategy is indispensable [11].

The DT architecture currently facilitates the amalgamation of emergent technological capabilities, including blockchain, machine learning, and predictive analytics, thereby elevating the status of architects and facility managers to strategic stewards of the building lifecycle [9]. Occupying this proactive role necessitates an iterative process of skill enhancement as the technological composition of the built environment continues to evolve.

By deliberately transferring to these digital paradigms, architectural and facilities management practitioners are equipped to confront pressing demands associated with urban sustainability, while concurrently optimizing the efficiency and efficacy across the lifecycle of the built environment. Such a deliberate transition simultaneously fortifies the professional relevance of these roles vis-à-vis rapid technological evolution and substantively contributes to the propagation of sustainability across the construction sector.

4.3 Integration of Digital Twin at the Community Scale for Sustainable Urban Planning

Deploying Digital Twin (DT) technology at the community scale holds particular promise for the construction and operation of intelligent, adaptive, and sustainable urban planning infrastructures. Comparative analysis of Helsinki and Sejong urban laboratories has shown that DT generates high-fidelity spatial-temporal simulations that quantify not only carbon emissions, but also energy performance, mobility demand, and projected population growth [1, 12]. Consequently, decision-makers can appraise the ecological footprint of hypothetical development trajectories prior to the mobilization of legal and financial commitments, thus embedding precautionary governance early in the planning workflow.

For emergent tropical megacities such as the Nusantara Capital City (IKN), the DT platform presents a vehicle for engineering urban lattices that are simultaneously resilient to projected climate perturbations, optimized for the circular use of energy and materials, and attuned to the adaptive capacities of resident communities. Technology orchestrates the coupling of architectural form, infrastructural networks, and sociocultural rhythms, thereby furnishing a coherent vessel for the polycentric and systemic spatial agendas that are characteristic of contemporary urbanization [6].

Yet the difficulties of embedding Digital Twin (DT) technologies within the community framework are manifestly more intricate than those involved with isolated building deployments. A composable, interoperable architecture—anchored by open data regimes, pervasive digital infrastructure, and cross-government collaboration—is considered a sine qua non for success [3]. Many developing urban environments, however, display chronic deficits in these domains, consequently erecting formidable obstacles to the wider dissemination of DT beyond the parcel scale [11].

Against this backdrop, a pilot intervention of medium scale—delimited to university campuses, multifunctional residential precincts, or strategically selected community amenities—offers a calibrated tactical entry point. It has been contended that the socio-institutional dimension—characterized by substantive citizen engagement and transparent governing processes—constitutes the bedrock of durable urban digitalization [12]. The Digital Twin framework is positioned as an enabler of integrative, long-range sustainable urban planning (see Fig. 2).

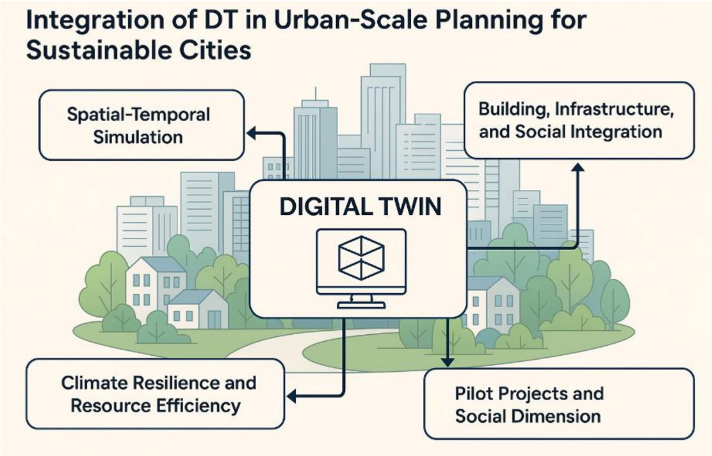

Fig. 2. Integration of Digital Twin in Sustainable Urban Planning.

Digital Twin (DT) operates as an integrative platform encompassing spatial-temporal simulations, infrastructural and social coupling, resource efficiency, and climate resilience. Moreover, it undergirds and advances pilot initiatives that deliberately incorporate social criteria, thereby signalling that the Digital Twin paradigm extends beyond mere technical optimisation. Its legislative commitment to balancing technological, environmental, and societal factors establishes the normative substrate upon which resilient, adaptive urban systems of the future are constructed.

When urban planners employ DT as an analytical and operational instrument, they are granted heightened capacity to diagnose and to modulate the complex challenges of urbanisation. The resulting capabilities position cities to evolve into sustainable, adaptive entities that respond dynamically to the evolving expectations of their populations, while also containing their ecological footprint.

4.4 Challenges and Opportunities for Implementation in Tropical Regions

Implementation of Digital Twin (DT) technology in tropical environments faces multifaceted barriers, including constrained financing, the scarcity of robust sensor and Internet of Things (IoT) networks, and a construction workforce marked by limited digital competency [1, 11]. Furthermore, prevailing DT solutions are predominantly calibrated for temperate zones and thus inadequately factor in tropical contingencies of elevated temperature, persistently high humidity, and unreliable power supply [3, 9].

Nevertheless, the context of the tropics is also replete with avenues for designing Digital Twins that are intrinsically anchored to the regional context. These include the strategic deployment of cost-efficient passive sensors, the leveraging of open-access software that can be iteratively modified by local developers, and the assimilation of indigenous construction strategies—such as passive cooling via natural ventilation and the employment of locally sourced, climate-responsive materials—thereby raising the pertinence and operational resilience of DT functionalities [6].

Efficacy of digital transformation undertakings in the tropics is governed more by sociotechnical congruence than by technological primacy. Pilot development of Digital Twin models in programmes dedicated to affordable suburban housing, basic educational infrastructure, or the revitalisation of communal amenity space is thus advocated as a pragmatic stratagem for generating iterative, locally attuned sustainability narratives that can scale in tropical climatic zones [12].

Thus, a focused strategy that is contextual, economically accessible, and rooted in communities is imperative for the viable integration of Digital Twin technology in tropical contexts. If these measures are applied earnestly and within a systematic framework, Digital Twin can transcend the status of a mere technical novelty and emerge as a decisive mechanism for cultivating built environments that are resilient, socially inclusive, and responsive to climate variability. This framework not only resolves the urgent deficiencies in technology and infrastructure but evidently cultivates active civic engagement and strengthens local skills, rendering the pursuit of sustainable urban growth in tropical environments considerably more achievable.

In conclusion, the venture of deploying Digital Twin technology in tropical regions is beset with formidable challenges, yet the horizon is equally replete with avenues for inventive practice and civic advancement. If these dimensions are judiciously coordinated, the result is the reconfiguration of living conditions in ways that elevate resident well-being and concurrently limit ecological disturbance.

4.5 Digital Twin: Global Practices and Tropical Adaptation

To understand the practical implementation of Digital Twin (DT) within the context of architecture and building governance, several international case studies have been analyzed based on application focus, resulting impacts, and their potential adaptation in tropical regions. These case studies reflect the diversity of DT approaches, spanning from building scale to city-wide implementations, offering valuable insights related to opportunities for similar technology application in tropical contexts that present unique climatic, social, and technical challenges. Key points to consider include:

(i). Contextual Adaptability in Tropical Climates: The NTU project in Singapore demonstrates that Digital Twin can operate effectively in humid tropical conditions. Real-time monitoring of temperature, humidity, and occupancy supports energy efficiency, which is highly relevant for tropical countries facing similar challenges. This shows that local climate and environmental conditions can be seamlessly integrated into DT systems to optimize building performance.

(ii). Scalability and Replicability in Tropical Urban Areas: Case studies from Helsinki and Sejong highlight how DT can be utilized for large-scale urban planning and infrastructure integration. This opens significant opportunities for replication in developing or redesigned tropical cities, such as the Nusantara Capital City (IKN). Effective scaling means that lessons learned from temperate or more developed regions can be adapted and implemented in emerging urban centers in the tropics.

(iii). Enhancing Efficiency and Comfort in Tropical Buildings: The Edge Olympic Building emphasizes the importance of data-driven energy management, lighting control, and ventilation. Adapting similar technologies in tropical contexts can reduce electricity consumption for cooling in offices and public facilities. By leveraging DT, building managers in tropical weather can optimize indoor climates, leading to enhanced occupant comfort and lower energy costs.

(iv). Relevance to Tropical Educational Institutions: Studies from Cambridge and NTU highlight the potential of DT in optimizing space and managing educational buildings. This is particularly relevant for universities or schools in tropical areas dealing with operational challenges due to high temperatures and space density. Implementing DT could aid in optimizing classroom environments, thereby improving learning outcomes and operational efficiency.

(v). Need for Technology and Policy Local Adaptation: While technically feasible, all case studies indicate that the success of DT implementation greatly depends on its adaptation to local conditions, including climate, digital infrastructure, and human resource capabilities. A context-sensitive approach to DT is essential for success in tropical regions, emphasizing the need to consider local community needs, available resources, and specific environmental challenges.

This study yields several important findings that have the potential to contribute novel insights to the literature on Digital Twin (DT) in built environments, particularly within the tropical context (see Fig. 3).

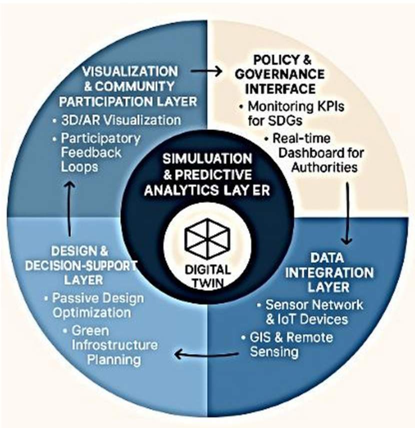

Fig. 3. Adaptive Digital Twin Framework for Tropical Urban Resilience

(i). Context-Sensitive Digital Twin Concept for Tropical Regions: One of the main innovations of this study is the emphasis on the importance of a context-sensitive approach, which involves developing DT specifically tailored to the climatic, social, and infrastructural characteristics of tropical environments. This approach has not been extensively examined in literature that predominantly focuses on the contexts of developed countries.

(ii). DT Adaptation Model Based on Tropical and Sub-Tropical Case Studies (see Fig. 2): By analyzing projects such as NTU in Singapore, the Edge Olympic Building, as well as Sejong and Helsinki, this study constructs a DT adaptation model relevant to tropical countries. This model integrates real-time environmental monitoring, energy efficiency, and data utilization for space management, making it highly applicable within tropical contexts.

(iii). Potential for Replication in Developing Tropical Cities: This study highlights the opportunities for implementing Digital Twin (DT) in new tropical cities such as the Nusantara Capital City (IKN). The novelty lies in the recognition that DT is not only relevant for smart cities in developed countries but can also be contextually replicated in tropical regions that are in the planning and growth phases.

(iv). Integration of Local Social and Cultural Dimensions in DT Design: This emphasizes that the success of DT in tropical areas is significantly influenced by the integration of social sustainability principles, community participation, and an understanding of local culture. This creates a new direction in DT research, which has so far been dominated by technical aspects

5 Conclusion

The deployment of Digital Twin (DT) technology across diverse geographical and institutional settings reveals pronounced opportunities to improve operational efficiency, environmental sustainability, and responsiveness of constructed environments. Empirical examinations conducted in sites as varied as Nanyang Technological University in Singapore and Sejong Smart City in South Korea confirm that DT supports differentiated objectives: live monitoring of energy consumption, data-centric sector-level urban metabolism review, and programmable enhancement of spatial and phenomenological comfort. Collectively, the evidence suggests that, notwithstanding the divergent tropical meteorological regimes and social geographies that such explorations confront, the conceptual architecture of DT retains a transferable core, which can be recalibrated to the specific climatic chronotopes and governance arrangements characteristic of tropical settings.

Within emergent tropical-market countries, Indonesia epitomises the prospective domain wherein Digital Twin can recalibrate the conventions of pragmatic and speculative practice. Here, architectural design and urban policy stand to be considerably enriched when the DT methodology is rendered as a coadaptive, climate-conscious artifact governed by empirical datasets, participatory governance, and ecological frameworks. Such methodological recalibration is rendered operational only when epistemological presumptions of conventional practice are evidenced, inclusive of indigenous epistemic repositories, spatial and social maternity of local collectives, and contemporary readiness of digital market. The resulting reformulation posits Digital Twin, not simply as a testimony to global digital penetration, but rather as an incisive instrument of agency by which adaptive, resource-respectful, and regionally informed settlements can be materialized.

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