



Indonesia's Transition Toward Digital Twin in Smart Cities Development: An Integrative Review

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Abstract

Background: Indonesia's rapid urbanization, particularly in megacities like Jakarta, requires innovative solutions for optimizing urban infrastructure and sustainability. Digital Twin (DT) technology presents a promising approach to improving energy efficiency in smart buildings and advancing the smart city agenda. However, challenges in infrastructure, workforce skills, and regulatory support hinder its implementation.

Objective: This study reviews the application of DT technologies in Indonesia's smart city development, focusing on energy efficiency in smart buildings. It explores DT adoption, identifies barriers, and proposes strategies for overcoming these challenges.

Methods: An integrative review following PRISMA guidelines was conducted, analyzing 260 peer-reviewed articles published from 2002 to 2025. The review examined global trends, policy alignment, DT applications, enabling technologies, and barriers in Indonesia.

Finding: DT technology is increasingly applied in smart building energy management in Indonesia, including smart building monitoring and dynamic construction projects. However, adoption is limited by challenges such as inadequate IoT infrastructure, high investment costs, fragmented governance, and lack of technical expertise. The Indonesian government's 100 Smart Cities initiative offers a supportive policy framework for DT implementation.

Conclusion: The study highlights the potential of DT to enhance energy efficiency and support sustainable urban development in Indonesia. It recommends addressing barriers through coordinated policies, investments in IoT infrastructure, and human capital development. Future research should focus on longitudinal studies and cross-city comparisons to evaluate DT's effectiveness in urban sustainability.

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INTRODUCTION

The challenges posed by global urbanization and population growth are fundamentally reshaping development strategies aimed at fostering equitable and sustainable growth. This pressure is acutely felt in metropolitan areas like Jakarta and other megacities, where rapid urban expansion necessitates the adoption of innovative technologies and transformative approaches to optimize urban infrastructure. The integration of the smart city concept emerges as a pivotal solution to address and mitigate the multifaceted challenges of urbanization, while simultaneously minimizing its adverse environmental impacts (Suryawan et al., 2024).

The realization of a sustainable environment within the smart city framework was initiated in 2017 through a government-led program aimed at establishing 100 Smart Cities across Indonesia. The program encompasses a comprehensive assessment process involving 70 cities and districts, aligning with the Ministry of Public Works' Green City initiative and the

Sustainable City Index, as evaluated by the Ministry of National Development Planning of the Republic of Indonesia. This endeavor is closely aligned with the National Policy and Strategy for Urban Development (2015–2045) and the fulfillment of the 17 UN SDGs, which prioritize the creation of sustainable and competitive cities ([Ministry of Communication and Digital Republic of Indonesia, 2017](#)).

The concept of smart cities, or cyber cities, presents a transformative opportunity for Indonesia to effectively manage its development programs by addressing critical factors such as human resource readiness, energy efficiency, infrastructure development, and the sustainability of these initiatives. The pursuit of a smart environment, characterized by robust and sustainable environmental governance, is exemplified through innovative energy-saving measures, including the integration of solar power in public spaces and facilities. This strategic approach not only enhances energy efficiency but also fosters a resilient urban ecosystem ([Ministry of Communication and Digital Republic of Indonesia, 2017](#)).

The building sector itself plays a significant role in global energy consumption, greenhouse gas (GHG) emissions, and resource utilization. Research indicates that buildings account for approximately 40% of total energy consumption and contribute to 30% of global CO₂ emissions. In Indonesia, the impact is particularly pronounced, with the building sector responsible for 4.6% of total energy consumption and 24% of energy-related carbon dioxide emissions in 2021. Consequently, the decarbonization of urban areas emerges as a critical strategy for mitigating carbon emissions and fostering sustainable development. By prioritizing energy efficiency and sustainable practices within the building sector, Indonesia can make substantial strides toward achieving its environmental goals and ensuring a resilient future for its urban landscapes ([Institute for Essential Services Reform, 2024](#)).

While the significance of digital twins (DT) in advancing sustainable urban development is increasingly recognized in global literature, research specifically addressing their application in smart buildings within the context of Indonesia's emerging smart cities remains notably scarce. This gap can be attributed to several factors, including insufficient training programs and a lack of technical expertise, which hinder the effective implementation of DT technologies. Moreover, the absence of robust government policies and incentive structures further limits the scalability and integration of DT solutions aimed at achieving substantial operational carbon reductions, an essential component of impactful, technology-driven sustainability strategies ([Ohueri et al., 2023](#)).

To address the research gap, this study aims to provide a comprehensive and integrative review of the application of digital twin (DT) technologies in enhancing energy efficiency within the framework of Indonesia's 100 Smart Cities initiative. The research addresses a critical knowledge gap through a detailed scientometric analysis, which systematically examines the current state of academic discourse. This analysis is guided by a series of research objectives designed to explore thematic trends, technological adoption, and policy alignment in the implementation of digital twins for sustainable urban energy management.

This study aims to provide a comprehensive and integrative review of digital twin (DT) technologies in the context of Indonesia's smart city development by: (1) critically examining prevailing global research trends and institutional contributions in DT for smart building energy efficiency; (2) analyzing the alignment of Indonesia's twin-transition and digitalization strategies with existing national policies and smart city frameworks; (3) identifying and evaluating current DT applications and enabling technologies for building energy systems in Indonesia; and (4) exploring the key barriers to DT adoption in Indonesia and proposing actionable strategies to enhance their future development and scalability.

LITERATURE REVIEW

Digital Twin for Urban Energy Optimization

The term Digital Twin (DT) was first introduced by Professor Michael Grieves in 2002 Ferré (2022), during a course on Total Product Lifecycle Management. The concept is also commonly referred to as a digital mirror or digital mapping, reflecting its core function of representing physical entities within a virtual environment ([Attaran & Celik, 2023](#)). Adamenkoa (2020) identified five functional roles of digital twin models encompassing the following: 1) To accurately replicate the properties, behaviours, and governing rules of the physical object, thereby

creating a precise digital representation. 2) To enable autonomous operation of the models, facilitating simulations of diverse object behaviours that can inform and guide the operation of the corresponding physical asset. 3) To support remote condition monitoring of assets, ensuring real-time insights into their operational state. 4) To provide predictive capabilities, allowing for the identification and mitigation of potential issues before they materialize. 5) To validate system performance prior to the final stage of the production process, ensuring design integrity and functional reliability.

Decades after Grieves introduced the concept of the digital twin in 2002, Digital twin applications are also increasingly developing in urban management, especially smart city development. Digital twin technology in urban management is also known as UDT (Urban Digital Twin) which is developing and expanding in parallel with the advancement of Artificial Intelligence (AI), the Internet of Things (IoT) and Big Data (BD) in smart cities with respect of environmental sustainability. UDT plays a role in data-based management and environmental sustainability efforts, offering innovative and environmentally friendly solutions to multifaceted aspects of smart cities (Weil et al., 2023).

Yang (2022) emphasized that the incorporation of smart building simulation technologies is instrumental in refining architectural design processes, ultimately enabling buildings to achieve near-zero energy consumption benchmarks. This technological foundation is further strengthened by the extensive adoption of photovoltaic integration, air-source heat pumps, and fresh air heat recovery systems, which collectively elevate the contribution of renewable energy sources and facilitate the efficient layering of energy use, known as cascade utilization. This offers building stakeholders detailed, real-time data on energy usage and environmental performance, thereby supporting informed decision-making for more sustainable urban development.

Digital Twin Adoption for Smart City in Indonesia

The smart city paradigm offers a promising framework for addressing sustainability challenges arising from accelerated urbanization. While earlier scholarly discourse predominantly framed smart cities within a sustainability-oriented context, contemporary perspectives have broadened this definition to emphasize the strategic integration of information and communication technologies (ICT). These technologies facilitate the convergence of diverse urban resources, fostering more intelligent, interconnected, and liveable urban environments (Tura & Ojanen, 2022).

As outlined in Indonesiabaik.id (2018), the Indonesian government's initiative, *The Indonesian Movement Towards Smart City*, represents a strategic effort to shape the nation's urban future toward becoming more sustainable and globally competitive between 2015 and 2045. To achieve that, the National Development Planning Agency (BAPPENAS) framed the multifaceted and cross-sectoral nature of urban challenges into a cohesive set of national urban development policies and framework: 1) Smart Governance entails the advancement of e-governance systems that promote participatory development planning and civic engagement in policy processes. 2) Smart Infrastructure focuses on the expansion of digital infrastructure, encompassing the development of integrated information and communication technology (ICT) networks, intelligent transportation systems, and IT-based urban management platforms. 3) Smart Environment emphasizes the use of ICT in environmental and natural resource management, including the implementation of digital tools for monitoring ecosystems and the promotion of renewable energy development. 4) Smart Living aims to enhance the quality of urban life through improved access to essential services such as education, healthcare, public safety, and media, thereby fostering a more inclusive and secure living environment. 5) Smart People refer to the cultivation of a technologically literate population through education, human resource development, research support, and the reinforcement of socio-cultural values within the community. 6) Smart Economy involves initiatives to stimulate economic innovation through city branding, the encouragement of entrepreneurship, and the integration of e-commerce into local and regional markets application of digital twin technologies (Asian Development Bank, 2025).

While the integration of digital twin technology into smart city initiatives holds considerable potential for enhancing energy efficiency and advancing sustainability objectives, its adoption within the Indonesian industrial context remains limited. Empirical studies have identified several persistent barriers to implementation, notably high investment costs,

technological complexity, and the need for more targeted governmental support, particularly in mitigating financial risks and addressing the uncertainties associated with technological deployment (Hutajulu et al., 2025).

METHOD

This study employed the Systematic Literature Review (SLR) methodology following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. SLR is a research methodology in collecting, identifying, and critically reviewing available research studies (Carrera-Rivera et al., 2022). Consequently, systematic literature review provides clarity for current research topics and forms the foundation of knowledge for future research (Martínez-Falcó et al., 2024).

SLR was employed to explore the pivotal role of digital twin technologies in enhancing energy efficiency within smart buildings, while addressing Indonesia's twin-transition strategies and the challenges of integration, ultimately providing strategic recommendations to advance the implementation of digital twins in the nation's smart city development agenda. We used SLR guidance by Tranfield.



Figure 1. PRISMA Flow Diagram of Systematic Literature Review Process
Source: Processed by Authors (2025) using PRISMA Guidelines

The initial database search retrieved 1,240 records. After removing duplicates and applying preliminary screening based on title and abstract, 460 full-text articles were assessed for eligibility. Following quality assessment criteria (Scopus-indexed, peer-reviewed, within thematic scope), a final sample of 260 articles was included in the synthesis. Excluded articles failed to meet at least one inclusion criterion, including insufficient methodological quality (n =

85), non-peer-reviewed status ($n = 68$), or thematic irrelevance ($n = 87$).

The research scope included articles published from 2002 to 2025. The year 2002 was chosen as the selection threshold because the term digital twin was introduced in that year, and its development in the literature has since been widely associated with smart cities. The selection of 2002 as the starting year was scientifically justified beyond the initial coinage of the term: it marked the foundational genesis of the Digital Twin concept by Grieves, a paradigm shift that constituted the earliest documented conceptual basis for all subsequent DT research in engineering, urban planning, and smart systems. Including literature from this formative period allowed for a longitudinal analysis of the concept's evolution from its industrial origins to its application in smart city energy systems—an analytical depth not achievable with a 10-year window.

This approach was consistent with established practice in systematic reviews examining the full lifecycle of emerging technologies Narong (2024) Rupasinghe (2024), and served the scientometric objective of tracing intellectual lineage and citation network formation over time (Datta, 2016). Furthermore, its development continues to attract more research on its usefulness on smart building adoption and advancement agenda (Rodemann a& Unger, 2018). In this study, the term digital twin used as a concept in Product Lifecycle Management is seen to be less relevant and more focused on the relationship of digital twins with smart building and smart city deployment.

The next step is the data selection process, which includes search strategy formulation, preliminary screening, and quality assessment as shown in Table 3 above. In the first stage, namely search strategy formulation, we used 18 keywords and combinations with Boolean operators and used the Scopus database to search for relevant studies. In the initial search, 584 articles were found.

The second stage is preliminary screening to filter articles by focusing on titles, abstracts, keywords, and inclusion and exclusion criteria. The preliminary screening specifically focused on five themes: 1) research trends for digital twins and their applications to smart buildings' energy efficiency and Indonesia's smart city agenda, 2) digital twin transition strategies that Indonesia faces in applying digital twins to smart buildings' energy efficiency, 3) the existing applications, emerging opportunities, and critical components necessary for the effective implementation of digital twins in building energy systems to support Indonesia's smart city goals, 4) the enabling technologies that underpin the application of digital twins, and how they contribute to the optimization of energy performance in smart buildings, 5) the key challenges hindering the adoption of digital twin technologies in Indonesia, and what strategies can be proposed to enhance their future development and scalability. This stage resulted in 353 articles.

The final step of this data selection process is quality assessment. To ensure the quality of the reviewed articles, the selected articles only used Scopus journals with high H-index criteria as a popular and prestigious measurement to evaluate the quality of the journals (Gupta et al., 2023). We chose empirical and non-empirical studies as type of studies in this SLR (such as conceptual research) to offer state-of-the-art from the perspective of philosophical analysis and framework development (Naeem et al., 2023). After carefully screening, this process resulted in 260 articles.

The final article sample was processed and synthesized through a narrative divided into the five themes mentioned above. The articles were selected based on article information (author, year of publication, abstract), document type, annual publication statistics, most cited authors, main keywords, renowned affiliations, publishing entities, theoretical and empirical background (supporting policies, applications, enabling technologies, and barriers to implementation).

RESULTS AND DISCUSSION

Results

In the present study, a total of 260 publications were analyzed, encompassing the most influential types of scholarly outputs and journal sources within the period spanning 2002 to 2025. The data presented in the following table details the distribution of document types and publishing entities. Among these publications, 254 were peer-reviewed journal articles, while 6 were conference proceedings. The analysis further identified 62 distinct author keywords and 212 indexed keywords. Notably, only 13 articles were authored individually, whereas the remaining 247 were the result of collaborative efforts, underscoring a predominant trend toward

multi-authorship in this field.

Annual publication statistics

Figure 2 shows the number of scholarly works published in the digital twin domain from 2014 to 2025. The data reveal a significant increase in the number of published works, especially from 2022 to 2024. This indicates growing research interest in digital twins, particularly regarding their implementation in smart building efficiency, in line with the development of smart cities in Indonesia.

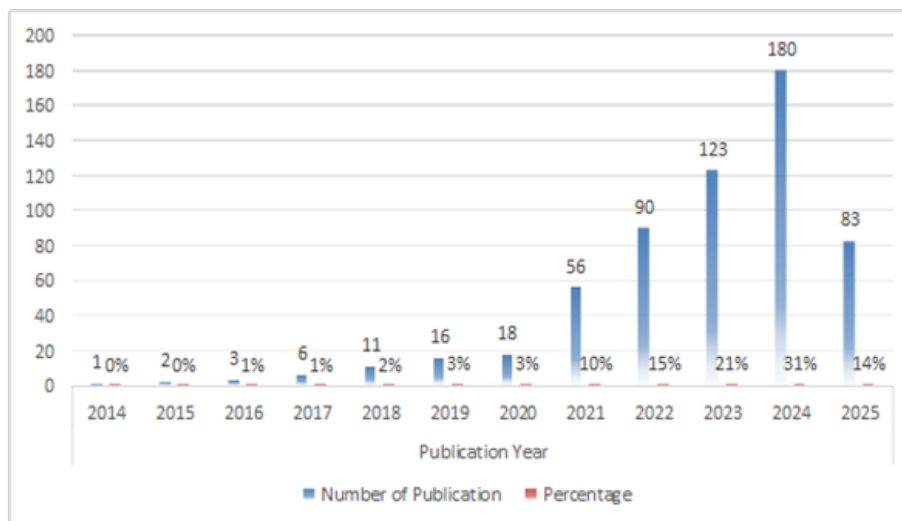


Figure 2. Annual publication (trends and performance)

Source: Processed Data (2025)

Most Cited Authors

Feriadi & Wong (2004) remains the most cited article in this dataset, reflecting a foundational concern with occupant thermal comfort in naturally ventilated Indonesian dwellings. Its use of field-based surveys to understand adaptive comfort behaviour in tropical housing conditions provided a practical framework that continues to inform energy-efficient building design across Southeast Asia. Its high citation count (578) indicates its lasting influence in both academic and applied sustainability discourse.

Joss (2013) contributed a major empirical milestone by mapping 178 eco-city initiatives across continents. Their work reframed sustainability transitions through the lens of urban experimentation and policy diffusion. With 284 citations, this article has shaped scholarly discussions on how eco-city models evolve globally, serving as a precursor to the smart city and digital twin movements where green infrastructure and technological governance increasingly intersect.

Dakwale (2011) delivered a timely systematic review of energy-efficient building technologies, including both passive and active design solutions. With 152 citations, their work remains a key knowledge source for those examining building performance improvements in emerging economies. It also laid the groundwork for later studies to explore how digital twin technologies can incorporate such strategies in real-time simulation environments.

Most Impactful Journals

Journal impact is assessed using a combination of established bibliometric indicators: (1) Scopus CiteScore, which measures average citations received per document published in the journal over a rolling four-year window; (2) SCImago Journal Rank (SJR), which accounts for both citation volume and the prestige of citing sources; (3) h-index, reflecting the journal's sustained scholarly influence based on cumulative citation impact of its published articles; and (4) Quartile ranking (Q1–Q4) within their respective subject categories, where Q1 denotes the top 25% of journals by SJR in their field (Gupta et al., 2023). Collectively, these indicators provide a multi-dimensional assessment of journal prestige, citation influence, and research impact.

Recent trends in scholarly publishing reveal a strong concentration of high-impact research emerging from Q1 Scopus-indexed journals, predominantly based in the United Kingdom, the Netherlands, Switzerland, and the United States. This geographic distribution reinforces the continued dominance of institutions and publishing bodies from the Global North in shaping digital twin, smart city, and sustainable urban development discourse.

A closer look at the journals shows that energy and engineering consistently serve as core thematic anchors. Prestigious journals such as *Applied Energy*, *Energy and Buildings*, *Energies*, and *Renewable and Sustainable Energy Reviews* position energy efficiency and building performance as critical domains for innovation. Simultaneously, the inclusion of titles like *Journal of Cleaner Production*, *Sustainability*, and *Sustainable Cities and Society* reflects the growing interdisciplinary integration of environmental science and sustainability within digital twin applications, particularly in urban climate adaptation and resilience-building.

The influence of computer science and digital technologies is equally prominent. Journals such as *IEEE Access*, *Electronics*, and *Sensors* underscore the central role of computational intelligence, IoT, and sensor integration in enabling real-time modeling, predictive analytics, and dynamic system optimization, all key features of digital twin platforms.

In terms of citation impact and research productivity, several publications stand out. *Energy and Buildings* and the *Journal of Building Engineering* have emerged as high-impact platforms, garnering over 1,200 citations each from a relatively modest number of publications, highlighting their efficiency in knowledge dissemination. Meanwhile, *Renewable and Sustainable Energy Reviews* leads in cumulative influence, with over 1,500 citations and an h-index of 464, underscoring its role as a flagship journal for sustainability innovation.

Most of the journals reviewed are classified in Quartile 1, signaling their high editorial standards, rigorous peer review processes, and global academic reach. Their high h-index values further demonstrate their sustained impact in advancing both foundational theory and applied knowledge in the field.

Most impactful keywords

Figure 3 shows keyword co-occurrence analysis. Keyword analysis is the most commonly used unit analysis in bibliometric networks, and many relationships can be found with the co-occurrence relationship of keywords in an article. VOS viewer is used to generate different maps based on those relationships (Rupasinghe et al., 2024). The figure below shows the most frequently used words such as “artificial intelligence”, “Internet of Things”, and “sustainability.” The colour code of the keywords reflects the novelty of scholarly interest in this topic. Brightly coloured keywords are associated with the most current topics. Keywords with darker colours are related to the most popular topics in the past few years (Narong & Hallinger, 2024).

exploratory, this theme may reshape governance, trust, and citizen participation in smart cities (Sadri et al., 2023).

Most Impactful Institution

The University of Indonesia has the highest number of publications and contributes as a strong base for the digital twin with a total of 18 publications, followed by Gadjah Mada University (UGM), Bandung Institute of Technology (ITB), and Bina Nusantara University (BINUS) with the same number of publications, 14.

Discussion

In synthesizing the selected literature, this study employs a comparative thematic analysis, systematically juxtaposing converging and diverging views across the reviewed articles on each thematic dimension. For each analytical theme, areas of scholarly consensus are identified alongside points of contention or ambiguity. For instance, while most reviewed studies concur on the transformative potential of IoT and AI as DT enabling technologies, there is notable disagreement regarding the readiness of Indonesia's regulatory infrastructure to govern their deployment. Similarly, studies agree that BIM forms a critical digital backbone for DT integration, yet differ in their assessments of how smoothly BIM-to-DT transitions can occur given current interoperability limitations in the Indonesian construction sector. This comparative approach enables a more nuanced and comprehensive interpretation, moving beyond mere description to critically engage with the state of knowledge on DT adoption in Indonesia's smart city context.

Supporting Policies and Frameworks of Digital Twin in the Context of Smart Building

The integration of digital twin technologies into smart buildings is essential to optimise energy efficiency and advance Indonesia's smart city initiatives. However, to achieve this, comprehensive policies and regulations are needed that are in line with national development goals and SDG goals (Berlian et al., 2025). As a matter of fact, despite a strong commitment to smart city development and sustainable urban planning in Indonesia, the implementation of digital twin technology in smart buildings has not been fully regulated and supported by explicit legal or policy frameworks.

While digital twins have emerged globally as transformative tools for real-time monitoring, predictive maintenance, and energy optimisation, their adoption in Indonesia is still in its early stages, often driven by isolated pilot projects rather than coordinated national initiatives. For example, in Indonesia's National Long-Term Development Plan (RPJPN) for 2025–2045, which emphasises the importance of strengthening the economy and improving quality of life by developing digital infrastructure and innovative public services.

This vision aligns with the integration of digital twin technologies in smart buildings, aiming to optimise energy consumption and reduce carbon footprints. However, it does not underscore the government's recognition of the importance of sustainable infrastructure, including energy-efficient buildings powered by digital twin technologies (Nugraha, 2024). Furthermore, the Indonesian government has established a regulatory framework to guide digital governance, notably through Presidential Regulation No. 95 of 2018, which defines digital government as a governance model that adapts to advances in information and communication technology. The governance model might not mention the pivotal role of digital twins for infrastructure, but it may serve as a foundation which is crucial for the successful deployment of digital twin technologies in smart buildings (Husni et al., 2022).

Current applications, enabling technologies, and key barriers of Digital Twin implementation

Indonesia's strategic transition towards smart cities is increasingly shaped by the deployment of digital twins (DT) solutions across various sectors. Drawing from recent studies, this discussion highlights four key applications of DT technologies that demonstrate both innovation and context-specific adaptation.

1. 3D Digital Twin for IoT-Based Smart Building Monitoring and Control

Despite advancements in smart building technologies, Indonesian implementations still struggle to deliver real-time, actionable insights to support responsive decision-making. To

address this, Wibowo (2024) propose a 3D digital twin dashboard that integrates IoT data to enhance monitoring accuracy, control precision, and user satisfaction. The system's architecture relies on IoT sensors, data processing units, 3D rendering engines, and an interactive user interface.

2. **Dynamic Digital Construction Monitoring for the New Capital City (IKN Nusantara)**
Construction processes in large-scale national projects often involve fragmented monitoring systems across multiple technologies. Yogi (2024) emphasize the role of dynamic digital twin solutions in facilitating real-time communication between physical construction elements and their virtual counterparts. In the case of IKN Nusantara, this approach enables better integration of BIM, GIS, IoT, and sensor data, thereby supporting synchronised progress tracking and decision-making.
3. **Digital Twin for Smart Campus Development**
As competition among Indonesian universities intensifies, the Smart Campus concept has emerged as a strategic necessity. Imbar (2023) present a Digital Twin Smart Campus Model that evaluates institutions based on their digital transformation maturity and "smartness" level. This model aids in improving university performance, cost and energy efficiency, and strategic planning. Its architecture integrates perception-decision-action systems with tailored readiness assessments focused on anthropocentric, systemic, and technological dimensions.
4. **Digital Twin for Optimizing Non-Conventional Roster Brick Prototypes**
In the realm of sustainable building design, occupant comfort is increasingly seen as a key performance indicator. Susanto (2025) explore the use of digital twin simulations and parametric design to optimise non-conventional roster bricks that improve daylighting, wind flow, and visual privacy. These passive design elements significantly enhance indoor environmental quality and energy performance.

Digital Twin Enabling Technologies in Smart Buildings

The integration of digital twin technology in smart buildings is underlined by several enabling technologies that collectively facilitate real-time monitoring, predictive analytics, and optimisation of building performance. Technologies such as IoT, Artificial Intelligence (AI), Cloud Computing, Building Information Modelling (BIM), Data Analytics and Visualisation, and Cybersecurity are instrumental in realising the potential of digital twins in increasing energy efficiency and supporting sustainable urban development. The following technologies play pivotal roles in shaping the architecture and functionality of DT applications, particularly in the context of smart buildings:

1. **Internet of Things (IoT)**
IoT provides the backbone of real-time data acquisition through sensors and connected devices. This continuous data stream supports dynamic DT model updates, enabling critical applications such as energy monitoring, HVAC optimisation, and occupancy tracking. However, widespread implementation is often constrained by issues of scalability, interoperability, and system reliability (Hermawan et al., 2024).
2. **Artificial Intelligence (AI)**
AI contributes significantly to the intelligence layer of DT by enabling predictive analytics, optimisation, and energy forecasting. In smart buildings, AI facilitates predictive control over lighting, HVAC systems, and anomaly detection. Nonetheless, the adoption of AI is challenged by concerns around data bias, model transparency, and trust (Prihatmanto et al., 2024).
3. **Cloud Computing**
Cloud infrastructure is crucial in hosting digital twin platforms, providing storage, facilitating remote access, and ensuring real-time integration across systems. It enables mobile-based and multi-user interactions with building systems. Despite these advantages, limitations include data latency, cost, and dependence on stable connectivity, issues still prevalent in various Indonesian urban regions (Hermawan et al., 2024).
4. **Building Information Modelling (BIM)**
BIM offers a structural digital representation of physical assets, serving as a foundational platform for DT development. It is extensively applied in structural modelling,

construction planning, and infrastructure monitoring. Nevertheless, BIM implementation often faces limitations due to the complexity of model updates and integration challenges with IoT data streams (Kusdiwanggo et al., 2024).

5. Data Analytics & Visualization

This component enables decision-making based on large volumes of DT data. Visualisation tools and analytics dashboards are essential for stakeholder communication and energy consumption tracking. However, such tools require careful design to ensure usability and relevance for diverse users. Complexity and the need for stakeholder-specific insights remain key concerns (Budiono & Budiarto, 2024).

6. Cybersecurity

Ensuring the protection of data, platforms, and communication protocols is fundamental in DT ecosystems. Cybersecurity safeguards smart building infrastructures from potential cyber threats, particularly in IoT and cloud-integrated environments. As smart systems become increasingly interconnected, sophisticated attacks and vulnerability risks demand proactive and adaptive defence mechanisms (Siswipraptini et al., 2024).

7. Key Barriers Hindering the Adoption of Digital Twin Technologies in Indonesia

Indonesia's smart city transformation via Digital Twin (DT) technology faces a constellation of interrelated barriers. These challenges span technological foundations, institutional frameworks, economic feasibility, human capacity, ethical concerns, and urban disparities, each reinforcing the other in limiting scalable and inclusive implementation.

8. Technological Limitations Reflect Foundational Readiness Gaps

The lack of widespread Internet of Things infrastructure and real-time data acquisition systems hampers the responsiveness and accuracy of digital twin models. Low interoperability standards, where platforms and devices lack integration protocols, undermine seamless collaboration among multiple stakeholders in smart city projects. Moreover, limited artificial intelligence and data analytics capabilities reduce the potential for real-time optimisation and predictive modelling, while aging building structures are difficult and expensive to retrofit with digital twin-compatible technologies (Qi & Tao, 2018).

9. Governance Fragmentation and Policy Vacuums Undermine Scalability

Indonesia's urban governance remains fragmented, with overlapping roles across ministries, local governments, and developers, creating bureaucratic inertia and weak coordination. The absence of national standards or regulatory frameworks for DT adoption leads to inconsistent deployment and poor benchmarking. In addition, the lack of fiscal incentives (e.g., tax breaks or subsidies) and lax enforcement of green building regulations reduce the motivation of private actors to invest in energy-efficient, DT-enabled infrastructure (Meijer & Bolivar, 2015).

10. Economic Uncertainty Constrains Private and Public Investment

Digital twin systems require substantial initial investment in hardware (e.g., sensors), software platforms, cloud services, and highly skilled labour. This limits adoption primarily to wealthier urban areas or projects backed by international donors. Additionally, the return on investment (ROI) from digital twin systems, such as through energy savings or predictive maintenance, is long-term and uncertain. As such, both public and private actors may hesitate to commit financial resources (Opoku et al., 2023).

11. Human Capital Deficits Stall Domestic Innovation

Indonesia faces a critical shortage of professionals with expertise in BIM, AI, IoT, and urban informatics, disciplines essential for designing, deploying, and maintaining digital twins. This reliance on foreign experts inflates project costs and reduces local ownership. Moreover, resistance to technological change among public officials and facility managers impedes adoption, indicating the need for systemic digital capacity-building across institutions (World Bank Group, 2021).

12. Data Governance and Ethical Uncertainties Erode Trust

Digital twin systems rely heavily on continuous data exchange involving occupancy patterns, infrastructure usage, and personal movement. Without clear regulations on data privacy, cybersecurity, and ownership rights, such systems expose municipalities and citizens to legal and ethical risks. These issues are particularly pressing under public-private partnership (PPP) models where data may be shared across entities with competing interests

(Kitchin, 2016).

CONCLUSION

This study has examined Indonesia's transition toward Digital Twin (DT) adoption within its smart city development framework, addressing four interrelated research objectives. First, the global bibliometric analysis reveals a sharp upward trajectory in DT research output from 2017 onward, with dominant contributions from Q1 Scopus journals in energy, engineering, and computer science. The University of Indonesia leads institutional productivity domestically, while key thematic clusters spanning building energy efficiency, AI-driven optimization, BIM-based design, smart city governance, and blockchain-enabled data security reflect the interdisciplinary nature of DT research. Second, Indonesia's twin-transition strategies, articulated through the 100 Smart Cities initiative and national digitalization roadmaps, demonstrate a broadly favorable policy orientation toward DT adoption; however, the absence of DT-specific regulatory standards and fragmented governance across ministries continues to impede coherent national implementation.

Third, current DT applications in Indonesia span smart building monitoring via IoT-based 3D dashboards, dynamic construction monitoring for the IKN Nusantara capital project, smart campus development, and sustainable building façade optimization—each enabled by key technologies including IoT, AI, cloud computing, BIM, and data analytics. Fourth, adoption remains constrained by a constellation of barriers: inadequate IoT infrastructure, policy fragmentation, high upfront investment costs, human capital shortages in BIM and urban informatics, and unresolved data governance and cybersecurity concerns. Addressing these barriers through coordinated policy, strategic investment, and capacity development is essential for DT technologies to fulfill their transformative potential within Indonesia's smart city agenda.

Beyond these empirical findings, this study offers a novel theoretical contribution by integrating scientometric analysis, policy alignment review, and enabling technology mapping into a unified analytical framework—an approach not previously undertaken in the literature on DT adoption in Indonesia. This integrative methodology serves as a replicable template for researchers investigating emerging technology adoption in developing-country urban contexts. Future research should prioritize longitudinal studies tracking real-world DT implementation outcomes, cross-city comparative studies within Indonesia, and the development of context-sensitive performance metrics for evaluating DT effectiveness in energy efficiency and urban sustainability.

This study highlights the theoretical implications by emphasizing the challenges of using digital twins in smart city environments, particularly in building systems' operational and maintenance management. It provides a foundation for further research on digital twin resilience in smart city development. Policy recommendations include developing a National IoT Infrastructure Roadmap, adopting open standards for interoperability, establishing a National Digital Twin Task Force, and creating investment models to encourage public-private partnerships. Additionally, human capital initiatives such as national upskilling programs and collaborations between industry and academia are proposed. The study also suggests developing a Smart Building Data Governance Framework and mandating cybersecurity-by-design for new systems. Tiered implementation strategies for smart cities and urban inclusivity audits are also recommended. Future research could explore integrating digital twins with legacy infrastructure, progressing from conceptual models to real-time simulations, effective policy instruments for energy management, and identifying the skills needed for professionals in the digital twin sector.

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AUTHOR CONTRIBUTION STATEMENT

Mombang Sihite conceptualized the research, developed the methodology, and led the writing process of the manuscript. Aisyah Pia Asrunputri contributed to the systematic literature review, data analysis, and provided critical revisions to the manuscript. Both authors have reviewed and approved the final version of the manuscript.

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