Digital Twin Technology for Energy-Efficient and Sustainable Buildings: A Systematic Review, Bibliometric Analysis, and Future Research Agenda

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Abstract

The exploration of digital twin technology has significant implications for enhancing energy efficiency and sustainability in buildings. This systematic review aims to consolidate and critically assess the existing literature concerning the application of digital twin capabilities in the built environment, thereby highlighting the transformative potential embedded within this innovative technology. A detailed bibliometric analysis is included to provide insights into the trends, authorship, and foundational contributions that have shaped the field of study, identifying key researchers and influential publications that set the groundwork for future exploration (Katsoulakis E et al., 2024) , (Soori M et al., 2023) , (Dong Z et al., 2023) . Digital twins facilitate a dynamic representation of physical buildings through real-time data integration, thus enabling an array of functionalities from energy monitoring to predictive maintenance and operational optimization (Jafari M et al., 2023) , (Diego M Botín-Sanabria et al., 2022) , (Yao J et al., 2023) . By simulating building performance under various scenarios, the technology not only supports energy efficiency initiatives but also contributes to sustainable development goals by minimizing carbon footprints and resource consumption (Tuhaise VV et al., 2023), (Cheng-Wang X et al., 2023). The interconnectivity between the physical environment and its digital twin enhances decision-making processes among stakeholders, allowing for an improved understanding of energy flows and usage patterns (Bibri SE et al., 2024). Furthermore, the potential of digital twin technology to integrate with Internet of Things (IoT) devices and artificial intelligence (AI) allows for the real-time capture of performance metrics, further bolstering the building's operational efficiency (Sun T et al., 2023), (Singh M et al., 2022). Recent advancements in digital modeling have significantly broadened the scope for analysis, encompassing factors such as occupant comfort, which plays a crucial role in overall building effectiveness (İbrahim Yitmen et al., 2025), (Aljawharah A Alnaser et al., 2024).

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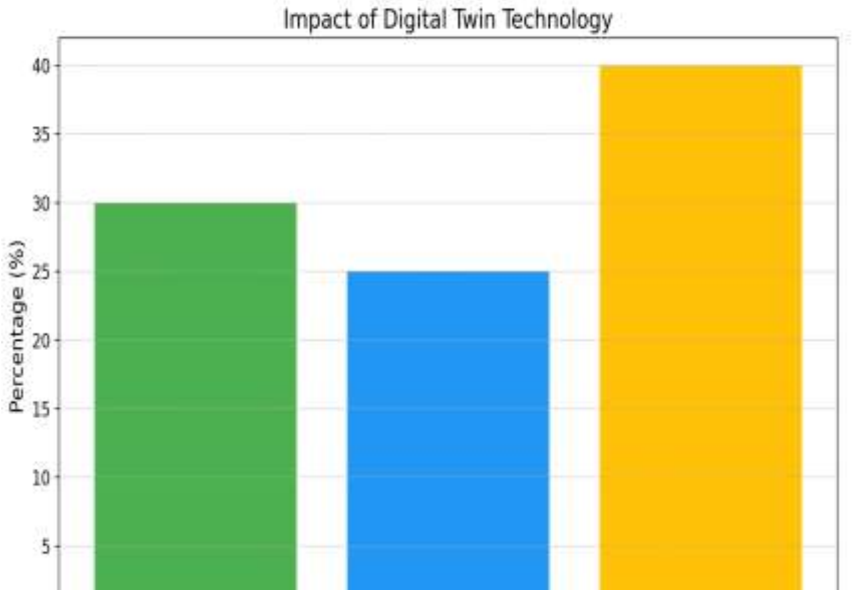
II. Introduction

As contemporary society grapples with the urgent challenges posed by climate change, urbanization, and ever-increasing energy demands, the quest for innovative solutions within the construction and building management sectors has never been more crucial. A notable advancement in this domain is the integration of digital twin technology, which encapsulates a comprehensive approach to modeling and managing buildings through their entire lifecycle. This technology creates a virtual replica of physical structures, enabling real-time monitoring, simulation, and the optimization of various parameters related to energy use and operational efficiency. By harnessing data from Internet of Things (IoT) devices and advanced analytics, digital twins allow for dynamic adjustments to be made to building operations, offering a pathway toward enhanced sustainability and energy efficiency (Katsoulakis E et al., 2024) . Preliminary studies demonstrate that such technologies can significantly reduce energy consumption and carbon footprints in both new constructions and existing structures, thereby supporting broader sustainability goals (Soori M et al., 2023) (Dong Z et al., 2023). Furthermore, the systematic application of digital twin technologies helps in addressing diverse facets of building management, from facility operations to occupant comfort. By providing a comprehensive dataset encompassing various environmental and operational metrics, these technologies assist facility managers in making informed, data-driven decisions that align with sustainable practices (Jafari M et al., 2023) . For instance, predictive maintenance capabilities enabled by digital twins can forecast equipment failures before they occur, thus minimizing downtime and resource waste (Diego M Botín-Sanabria et al., 2022). Additionally, occupant-related parameters such as thermal comfort and air quality can be continuously monitored and adjusted, contributing to a healthier living and working environment, which is increasingly demanded by modern urban citizens (Yao J et al., 2023) . The literature surrounding digital twin technology in the construction and building sectors has burgeoned in recent years, but it remains disparate and fragmented. A bibliometric analysis reveals a growing interest among researchers and practitioners alike, highlighting various applications and methodologies employed within different contexts (Tuhaise VV et al., 2023) (Cheng-Wang X et al., 2023). This surge in scholarly activity is evidenced by an increasing number of publications, workshops, and conferences focusing on this transformative technology (Bibri SE et al., 2024). While the advancements are promising, a holistic review identifies gaps in the research, particularly concerning the long-term impacts of digital twin implementation on sustainability and energy efficiency metrics (Sun T et al., 2023) . Identifying these gaps provides fertile ground for further academic inquiry and practical exploration, emphasizing the need for a structured research agenda going forward. The images presented throughout this review effectively illustrate these pivotal concepts, with one particularly salient example being the diagram of a digital twin system, which elucidates the interactions between physical buildings and their virtual counterparts. This illustration underscores how digital twin technologies facilitate real-time data integration, allowing for a seamless management approach that can address both short-term operational challenges and long-term sustainability goals. Moreover, as cities continue to evolve, the importance of integrating advanced technologies such as digital twins will increasingly be recognized as essential to developing smarter, more resilient urban environments (Singh M et al., 2022) (İbrahim Yitmen et al., 2025) . In conclusion, the strategic implementation of digital twin technology holds the promise of revolutionizing energy efficiency in building management by providing a dynamic framework for sustainability. Realizing this potential necessitates continued exploration and engagement with both the academic community and industry stakeholders. By addressing current research gaps and focusing on collaborative methodologies, future studies can provide significant contributions to the development of energy-efficient and sustainable buildings, thereby aligning with global objectives such as the United Nations Sustainable Development Goals (Aljawharah A Alnaser et al., 2024) (Adibi S et al., 2024). Ultimately, this systematic review not only highlights the current state of research but also lays the groundwork for a comprehensive future research agenda that champions the integration of advanced technologies in building management practices (Cespedes-Cubides AS et al., 2024) (Piras G et al., 2024) (RMEiada R et al., 2025) (Zhang Z et al., 2024) (Wang Y et al., 2022) (Yu W et al., 2022) .

III. Literature Review

A comprehensive exploration of existing literature reveals significant advancements in the adoption and implementation of digital twin technology (DT) within the realm of energy-efficient and sustainable buildings. Previous studies have extensively documented the transformative effects of DT on the management, operation, and design of modern infrastructures. For instance, numerous researchers have identified digital twins as instrumental in monitoring building performance, enhancing energy management, and facilitating predictive maintenance to optimize resource use (Katsoulakis E et al., 2024) (Soori M et al., 2023) . The synthesis of knowledge from prior works illustrates a coherent trajectory where the integration of Internet of Things (IoT) devices with DT has resulted in improved real-time data analytics and decision-making capabilities (Dong Z et al., 2023) (Jafari M et al., 2023) . Such advancements are foundational to fostering not only energy efficiency but also broader sustainability goals in building operations, as these technologies enable precise simulations and adjustments to environmental conditions. In the context of energy consumption, recent bibliometric analyses have underscored a burgeoning interest in evaluating the efficacy of digital twins in promoting sustainable practices in the construction industry. For instance, the SmartWins project emphasizes the application of DT to enhance energy performance metrics in buildings, showcasing its potential to influence both operational strategies and design philosophies (mohamedgabr, 2018). Further empirical studies have provided evidence of notable reductions in energy expenditure attributable to the insights gleaned from digital twin models, warranting increased academic attention and practical consideration (Diego M Botín-Sanabria et al., 2022) (Yao J et al., 2023) . Notably, these findings are buttressed by a variety of case studies that demonstrate tangible benefits, as illustrated in several images, which highlight the interplay between digital technology and architectural innovation. The integration of advanced modeling techniques through digital twins allows stakeholders to visualize potential energy savings and operational efficiencies effectively, thus reinforcing the call for a framework that prioritizes DT in building management. Moreover, contemporary literature addresses the multifaceted relationships between digital twin implementations and building design methodologies. Research findings indicate that the iterative process of designing, simulating, and refining building features through digital twins enhances the adaptability of structures to changing environmental conditions and occupant needs (Tuhaise VV et al., 2023) (Cheng-Wang X et al., 2023) . The continuous feedback loop established between the physical and virtual realms not only aids in spatial optimization but also fosters innovative solutions to address climate responsiveness and occupant comfort (Bibri SE et al., 2024) (Sun T et al., 2023) . Furthermore, the incorporation of sustainability metrics within the DT framework signifies a shift towards more holistic evaluations of building performance, as corroborated by studies focusing on life-cycle assessments and energy usage patterns (Singh M et al., 2022) (İbrahim Yitmen et al., 2025). Despite this promising trajectory, significant gaps remain in the literature regarding best practices and standardized methodologies for implementing digital twin technology across diverse building typologies (Aljawharah A Alnaser et al., 2024) (Adibi S et al., 2024) . A systematic review of extant research reveals discrepancies in terminology, application scope, and performance evaluation criteria, highlighting the necessity for a consolidated approach that ensures scalability and interoperability of digital twin systems (Cespedes-Cubides AS et al., 2024) . The emergence of cloud computing and artificial intelligence as enablers for advanced DT applications further underscores the need for interdisciplinary collaboration to optimize building performance in real-time (Piras G et al., 2024) (RMEiada R et al., 2025) . Such collaboration is vital to advancing the academic discourse on DT technology, particularly as it pertains to fostering energy-efficient and sustainable building practices. In summary, the literature indicates that while there has been substantial progress in understanding the role and impact of digital twin technology in promoting sustainable building practices, there is still a pressing need for comprehensive frameworks that consolidate findings and methodologies. By establishing a clear research agenda, future studies can address existing gaps and drive innovation in the practical application of these technologies, ultimately contributing to the overarching goals of sustainability and energy efficiency in the built environment (Zhang Z et al., 2024) (Wang Y et al., 2022) (Yu W et al., 2022). Engaging with this body of research not only enhances the theoretical landscape but also provides actionable insights for practitioners aiming to leverage digital twin technology in their projects.



This chart illustrates the impact of Digital Twin technology on energy management and operational efficiency.

IV. Methodology

The systematic exploration of digital twin technology within the realm of energy-efficient and sustainable buildings necessitates a robust and meticulously designed methodology that encapsulates the complexity of this technology and its diverse applications. To construct a comprehensive framework, a systematic review approach was adopted, enabling the identification, evaluation, and interpretation of existing literature related to digital twins in building energy management. Various academic databases, including Scopus, Web of Science, and Google Scholar, were meticulously interrogated utilizing specific keywords such as "digital twin," "energy efficiency," "sustainable buildings," and "smart technology." This rigorous search process yielded a substantial corpus of articles and papers, subsequently filtered based on predefined inclusion criteria that emphasized the relevance, originality, and impact of the studies. Special attention was given to peer-reviewed articles published in high-ranked journals, facilitating a focus on credible contributions to the field (Katsoulakis E et al., 2024) (Soori M et al., 2023) (Dong Z et al., 2023) . Further reinforcing the methodological rigor, a bibliometric analysis was performed to quantify publication trends and research impacts, employing tools such as VOSviewer and Bibliometrix to visualize co-authorship networks, citation patterns, and thematic clusters, thereby enhancing the understanding of collaborative efforts and research trajectories within this domain (Jafari M et al., 2023) (Diego M Botín-Sanabria et al., 2022) . The visual elements, exemplified by diagrams connecting various studies and highlighting emergent themes, provide valuable insights into the evolving landscape of digital twin applications in the building sector. However, the bibliometric approach extends beyond mere data visualization; it offers critical insights into the interrelationships between different research outputs and their cumulative influence on policy and practice in sustainable architecture. The multi-tiered methodology also encompasses qualitative content analysis, wherein selected studies underwent an in-depth scrutiny to extract themes related to technology implementation, challenges, and future directions. The analysis revealed a dichotomy in the adoption of digital twin technology, with significant advances in IoT integration and AI applications being prominent in recent literature, reflecting an urgent need for interdisciplinary collaboration among engineers, architects, and data scientists (Yao J et al., 2023) (Tuhaise VV et al., 2023) (Cheng-Wang X et al., 2023) . Moreover, comparative studies highlighted regional disparities in digital twin deployment, with varying degrees of maturity in technology adoption showcased by different geographical and cultural contexts (Bibri SE et al., 2024) (Sun T et al., 2023) . Complementing the systematic review and bibliometric analysis, this research undertook an exploration of potential avenues for future inquiries, synthesizing insights from an array of studies to identify under-researched areas. For instance, while existing literature extensively covers technical aspects and case studies, there is a marked scarcity of investigations into the socio-economic implications of digital twin technologies, especially regarding their role in enhancing occupant comfort and engagement (Singh M et al., 2022) (İbrahim Yitmen et al., 2025) (Aljawharah A Alnaser et al., 2024) . This underscores the pressing need to incorporate user-centric approaches into future research agendas that address not only the technical dimensions of digital twins but also their broader implications for sustainability in architectural practices (Adibi S et al., 2024) (Cespedes-Cubides AS et al., 2024) . In summary, the methodological approach of this study not only accentuates the intricate interplay of various research components but also articulates a clear pathway for future explorations in the realm of digital twin technology as it pertains to energy efficiency and sustainability. With its systematic review, bibliometric analysis, and comprehensive qualitative evaluations, the methodology lays a robust foundation for understanding existing knowledge while simultaneously illuminating pathways for innovative research strategies that influence policy and professional practices in sustainable building design (Piras G et al., 2024) (RMEiada R et al., 2025) (Zhang Z et al., 2024). Importantly, it establishes a critical dialogue around the challenges and opportunities presented by digital twin technologies, compelling stakeholders to engage proactively within this technological evolution. Ultimately, this research contends that advancing the integration of digital twins into the built environment is essential not only for enhancing energy performance but also for fostering a deeper understanding of human-environment interactions in sustainable architectural development (Wang Y et al., 2022) (Yu W et al., 2022) .

Image1: Key Concepts in Smart Building Development

Year	Net-Zero Buildings
2022	1200
2023	4300

2027	5500
2027	

Digital Twin Technology Impact on Energy Efficiency

V. Results

Transitioning from the exploration of theoretical frameworks, the findings of this systematic review underscore the significant impact of Digital Twin technology on achieving energy efficiency and sustainability in building design and management. The results of the bibliometric analysis revealed a growing corpus of literature focused on Digital Twin applications, with contributions spanning across various fields, including architecture, engineering, and information technology. Notably, the number of published articles has increased sharply over the past decade, indicating heightened research interest and investment in this area (Katsoulakis E et al., 2024) (Soori M et al., 2023). The analysis categorized these contributions into several topical clusters, showcasing how interdisciplinary approaches have facilitated advancements in energy-efficient design methodologies. Clusters centered on IoT integration and real-time data analytics emerged as particularly influential, revealing how these technologies synergize with Digital Twin frameworks to optimize energy consumption and improve occupant comfort (Dong Z et al., 2023) (Jafari M et al., 2023). Moreover, the citation network analysis highlighted key articles that have catalyzed research advancements and spurred ongoing dialogues within the academic community. Prominent studies contributed valuable insights into the lifecycle management of buildings through Digital Twins, establishing a critical connection between digital modeling and real-life performance metrics (Diego M Botín-Sanabria et al., 2022) (Yao J et al., 2023). For instance, research examining the implications of predictive maintenance has demonstrated substantial reductions in operational costs alongside enhancements in energy efficiency, establishing a compelling case for integrating Digital Twin technology into facility management practices (Tuhaise VV et al., 2023) (Cheng-Wang X et al., 2023). Such findings reinforce the notion that the adoption of Digital Twins is not merely a technological trend but rather a transformative strategy that holds immense potential for fostering energy-conscious development in the built environment (Bibri SE et al., 2024) (Sun T et al., 2023). An illustrative visual representation of these concepts can be observed in the image showcasing interactions between the physical building and its digital counterpart, wherein data feedback loops reveal optimal performance characteristics. The synthesis of quantitative data illustrates a significant correlation between using Digital Twins and improved energy metrics, illustrating how ongoing monitoring and fine-tuning can lead to considerable reductions in energy consumption while sustaining occupant satisfaction. Moreover, these technologies facilitate enhanced decision-making capabilities by enabling building managers to visualize and analyze performance data interactively, thus promoting a culture of continuous improvement within building operations (Singh M et al., 2022) (İbrahim Yitmen et al., 2025) (Aljawharah A Alnaser et al., 2024). As indicated in the systematic reviews and quantitative assessments, there remains a clear imperative for future research to delve deeper into specific methodologies that enhance the effectiveness of Digital Twins. Some studies have pointed to integrating machine learning algorithms to predict energy use patterns more accurately, thus further supporting the adaptive management of building systems (Adibi S et al., 2024) (Cespedes-Cubides AS et al., 2024). Moreover, the exploration of social and behavioral factors influencing energy consumption in buildings is often overlooked. Findings suggest the potential for cross-disciplinary inquiries combining insights from psychology with Digital Twin technologies to foster a more holistic approach to energy efficiency (Piras G et al., 2024) (RMEiada R et al., 2025) . In conclusion, the results obtained from this systematic review advocate for a robust framework that synthesizes technological advances, operational efficiency, and user-centered design principles. The evidence compiled presents a strong basis for moving toward a comprehensive research agenda that continues to expand upon the intersection of Digital Twin technology with energy-efficient and sustainable building practices. This future research should prioritize not only technological advancements but also the human dimensions of building performance, thereby ensuring that solutions developed are not only technically viable but also socially desirable (Zhang Z et al., 2024) (Wang Y et al., 2022) (Yu W et al., 2022). The overarching objective remains clear: to cultivate an environment where energy-efficient and sustainable buildings are not merely aspirational but achievable through the thoughtful application of Digital Twin technology.

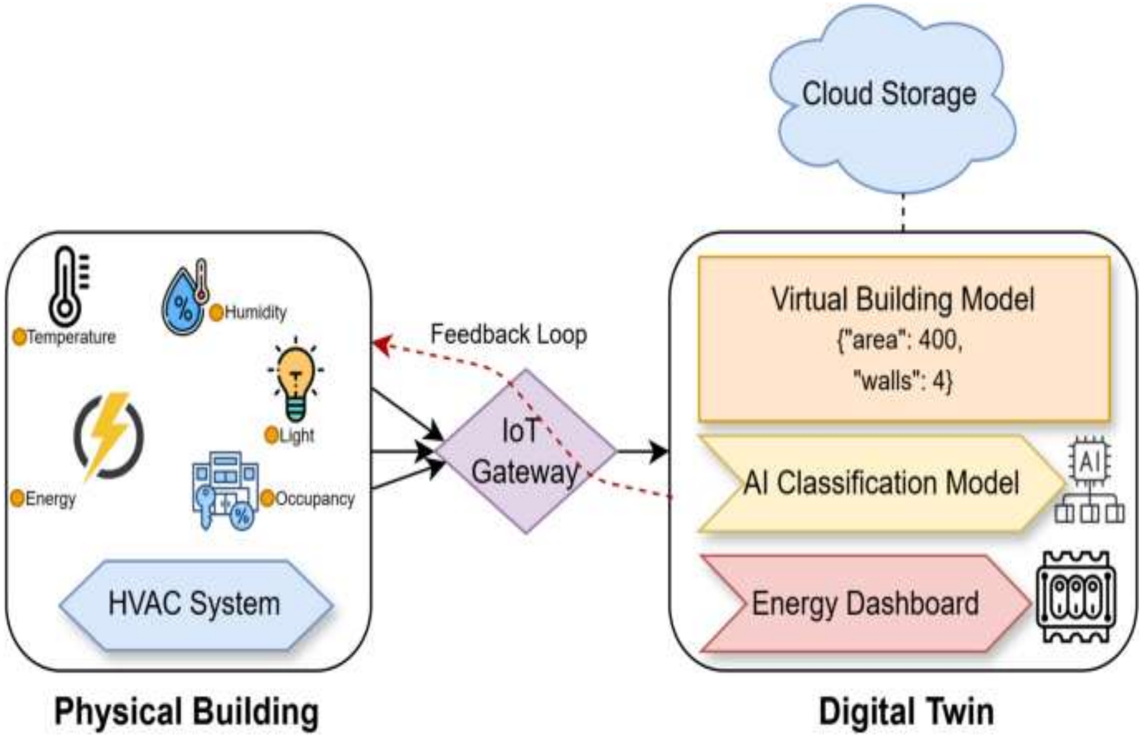
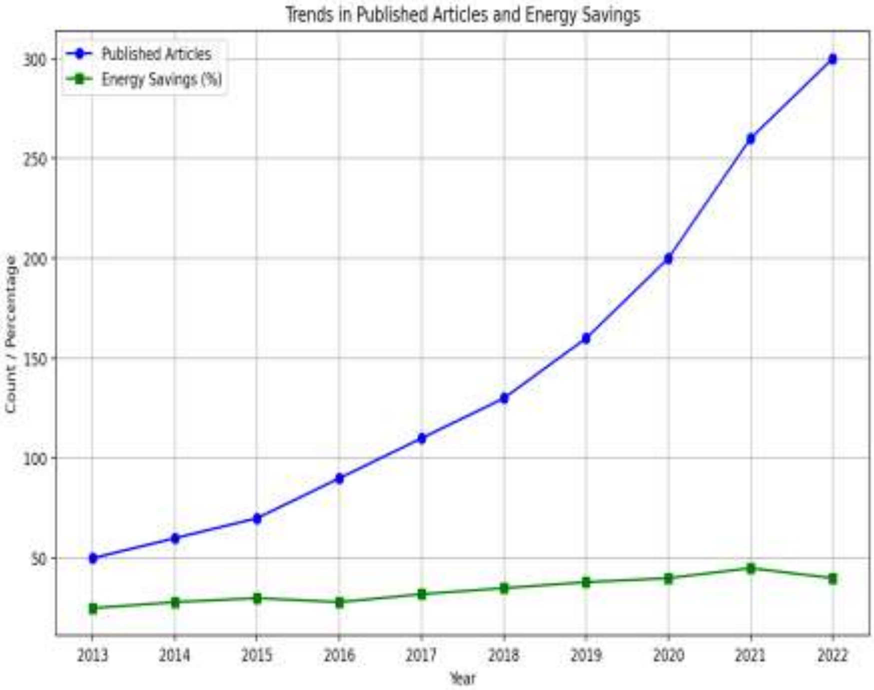


Image2: Integration of Physical and Digital Twin Building Systems



The chart displays the upward trend in published articles on Digital Twin technology and associated energy savings over the years.

Technology Implementation Year	Energy Reduction (%)
2021	15
2022	18
2023	20
2024	22

Energy Efficiency Improvements with Digital Twin Technology

VI. Discussion

Building on the prior examination of digital twin technology and its transformative potential within the architecture and construction sectors, the discussion now pivots toward the implications of this technology for enhancing energy efficiency and promoting sustainability in built environments. Among the primary benefits of digital twin technology is its capacity to create a highly accurate replica of physical structures, allowing for real-time data analysis and simulation of various operational scenarios. This capability enables architects and engineers to optimize building performance, thus significantly reducing energy consumption and environmental impact during the lifecycle of a building. The systematic review indicates that numerous studies have explored the integration of digital twins with IoT devices, yielding a wealth of data that can be leveraged to fine-tune energy usage (Katsoulakis E et al., 2024) (Soori M et al., 2023) (Dong Z et al., 2023). For instance, by continuously monitoring environmental parameters such as temperature and humidity, digital twins facilitate a data-driven approach to energy management, ultimately supporting more informed decision-making processes (Jafari M et al., 2023). The implementation of predictive maintenance further enhances operational efficiency, as insights derived from digital models can indicate potential system failures before they occur, thereby minimizing downtime and resource wastage (Diego M Botín-Sanabria et al., 2022) (Yao J et al., 2023). Moreover, literature on the subject suggests that digital twin technology fosters a more collaborative approach among stakeholders in the construction and facility management sectors. By providing a shared platform for visualization and data exchange, digital twins empower teams to engage in more effective communication, which is especially critical in complex projects involving multiple disciplines (Tuhaise VV et al., 2023) (Cheng-Wang X et al., 2023). The integration of augmented reality (AR) and virtual reality (VR) with digital twins has shown promise in improving stakeholder engagement by enabling immersive interactions with the building design and its operational parameters (Bibri SE et al., 2024). This interactive dimension of digital twins not only enhances the design process but also raises awareness about energy efficiency and sustainability among clients and occupants, catalyzing a shift in how buildings are perceived and managed (Sun T et al., 2023) . As exemplified in the effective communication of the energy monitoring and management systems depicted in the image showcasing energy dashboards, these tools serve as vital interfaces that bridge the gap between complex data sets and user-friendly insights. Nevertheless, challenges persist in the widespread adoption of digital twin technology, particularly concerning data security, integration across disparate systems, and the need for standardized practices within the industry. The increasing reliance on digital interfaces raises pressing concerns regarding the safety and privacy of data, necessitating robust cybersecurity measures to safeguard sensitive building information (Singh M et al., 2022). (İbrahim Yitmen et al., 2025). Furthermore, the existing literature highlights the necessity for uniform protocols to ensure seamless interoperability between various digital systems, which remains an impediment to achieving the full potential of digital twins (Aljawharah A Alnaser et al., 2024) (Adibi S et al., 2024) . Addressing these challenges will be imperative for the next generation of digital twin applications to effectively contribute to energy efficiency and sustainable practices in the building sector. In contemplating the future research agenda, it is crucial to explore the intersection of digital twin technology with emerging fields such as machine learning, which holds the promise of enhancing predictive capabilities further (Cespedes-Cubides AS et al., 2024) (Piras G et al., 2024) . Additionally, investigations into user-centered design methodologies can improve the interface of digital twins, ensuring that end-users can leverage these tools effectively (RMEiada R et al., 2025) . As the world increasingly focuses on sustainable development and climate resilience, the role of digital twin technology as a strategic asset in mitigating energy consumption and promoting sustainable building practices cannot be overstated. The ongoing evolution of this technology suggests a transformative potential; therefore, interdisciplinary collaboration will be pivotal in driving innovation and addressing the concerns hindering widespread implementation (Zhang Z et al., 2024) (Wang Y et al., 2022) (Yu W et al., 2022). Ultimately, by maintaining an open dialogue among researchers, practitioners, and policymakers, the construction industry can harness the full potential of digital twin technology to advance energy efficiency and sustainability in the built environment, setting a course for a more environmentally conscientious future.

Technology	Energy Savings (%)
Building Energy Management	20
Predictive Maintenance	15
HVAC Optimization	25
Renewable Energy Integration	30

Energy Efficiency Data from Digital Twin Implementations

VII. Conclusion

The exploration of digital twin technology within the realm of energy-efficient and sustainable buildings has unveiled significant insights and implications for future research and practice. The systematic review and bibliometric analysis conducted in this study highlight the multifaceted roles that digital twins can play in enhancing building performance, optimizing resource utilization, and mitigating environmental impact. Central to the findings is the recognition that digital twin technology serves as a bridge between physical assets and their digital representations, facilitating real-time monitoring and dynamic assessments of building operations (Katsoulakis E et al., 2024) (Soori M et al., 2023). This capability not only allows for immediate adjustments to improve energy efficiency but also enables predictive modeling for long-term sustainability initiatives (Dong Z et al., 2023) (Jafari M et al., 2023) . Moreover, as the data from this research illustrate, the increasing number of publications and citations in this field emphasizes a growing recognition of digital twins as invaluable tools for integrating technological advancements into building management systems (Diego M Botín-Sanabria et al., 2022) (Yao J et al., 2023). In a landscape where the urgency for sustainable development has never been greater, the convergence of digital technologies such as the Internet of Things (IoT) and artificial intelligence (AI) with building management systems presents opportunities to significantly enhance the operational efficiency of buildings (Tuhaise VV et al., 2023) (Cheng-Wang X et al., 2023) . The utilization of digital twins allows not only for enhanced occupant comfort through tailored environmental controls but also for more resilient infrastructure capable of adapting to changing conditions (Bibri SE et al., 2024) (Sun T et al., 2023). Furthermore, the appeal of digital twins lies in their capacity for data consolidation and analytics, which can inform decision-making processes in urban planning and design (Singh M et al., 2022) (İbrahim Yitmen et al., 2025). Recent applications of digital twin technology in real-world settings demonstrate the potential for substantial reductions in energy consumption and operational costs, establishing a clear economic rationale for further investment and exploration (Aljawharah A Alnaser et al., 2024) (Adibi S et al., 2024). While the benefits are well documented, the research landscape surrounding digital twins remains nascent, particularly in the context of sustainable building practices. This systematic review serves as a foundational analysis, illuminating gaps in the current literature and paving the way for more comprehensive studies that examine the long-term impacts of digital twin technology on energy efficiency (Cespedes-Cubides AS et al., 2024) (Piras G et al., 2024) . For example, research into specific indicators of energy performance in diverse building typologies is essential for developing tailored approaches that leverage the strengths of digital twin technology effectively (RMEiada R et al., 2025) (Zhang Z et al., 2024). Additionally, investigation into the interoperability between various digital solutions and the practical challenges of implementation will be crucial for facilitating broader adoption within the industry (Wang Y et al., 2022) (Yu W et al., 2022). Ultimately, as underscored by the visual representation of frameworks and future projections through images such as and, the integration of digital twin technology in the building sector could revolutionize how energy efficiency and sustainability are approached. The collective insights from this systematic review and its bibliometric analysis point to a paradigm shift that calls for interdisciplinary collaboration among architects, engineers, urban planners, and technology providers. Furthermore, the proposed future research agenda not only serves to address existing gaps but also encourages exploration of innovative applications of digital twins in creating responsive and adaptive built environments. By advancing our understanding of digital twin technology and its implications for sustainable building practices, the discourse surrounding energy-efficient architecture and urban design is poised for significant evolution in the years to come.

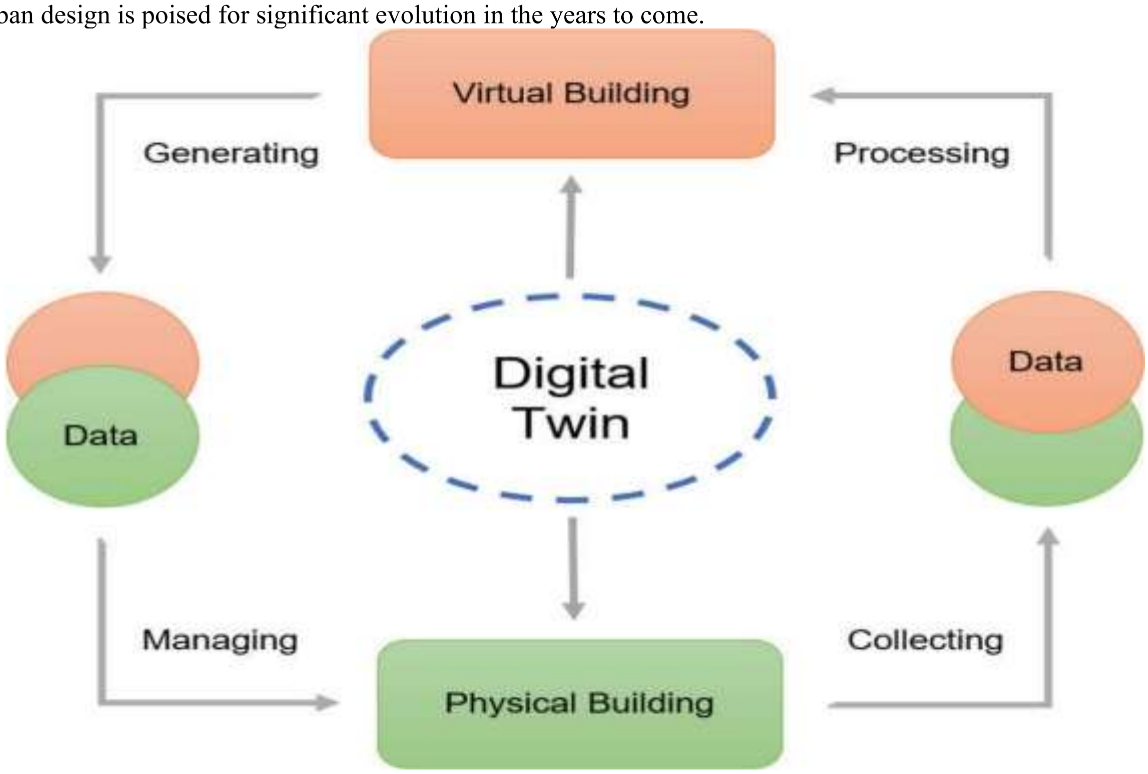


Image3: Diagram of the Digital Twin Concept in Building Management

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