








Review

Digital Platforms for the Built Environment: A Systematic Review Across Sectors and Scales

Michele Berlato ¹, Leonardo Binni ², Dilan Durmus ², Chiara Gatto ³, Letizia Giusti ⁴, Alessia Massari ⁴,
Beatrice Maria Toldo ¹, Stefano Cascone ^{5,*} and Claudio Mirarchi ³

¹ Department of Management and Engineering, University of Padua, 36100 Vicenza, Italy; michele.berlato@phd.unipd.it (M.B.); beatricemaria.toldo@studenti.unipd.it (B.M.T.)

² Department of Construction, Civil Engineering and Architecture, Marche Polytechnic University, 60131 Ancona, Italy; l.binni@pm.univpm.it (L.B.); d.durmus@pm.univpm.it (D.D.)

³ Department of Architecture, Built Environment, and Construction Engineering, Polytechnic University of Milan, 20133 Milan, Italy; chiara.gatto@polimi.it (C.G.); claudio.mirarchi@polimi.it (C.M.)

⁴ Department of Civil, Construction-Architectural and Environmental Engineering, University of L'Aquila, 67100 L'Aquila, Italy; letizia.giusti@graduate.univaq.it (L.G.); alessia.massari@graduate.univaq.it (A.M.)

⁵ Department of Civil Engineering and Architecture, University of Catania, 95125 Catania, Italy

* Correspondence: stefano.cascone@unirc.it

Abstract

The digital transformation of the Architecture, Engineering and Construction sector is accelerating the adoption of digital platforms as critical enablers of data integration, stakeholder collaboration and process optimization. This paper presents a systematic review of 125 peer-reviewed journal articles (2015–2025), selected through a PRISMA-guided search using the Scopus database, with inclusion criteria focused on English-language academic literature on platform-enabled digitalization in the built environment. Studies were grouped into six thematic domains, i.e., artificial intelligence in construction, digital twin integration, lifecycle cost management, BIM-GIS for underground utilities, energy systems and public administration, based on a combination of literature precedent and domain relevance. Unlike existing reviews focused on single technologies or sectors, this work offers a cross-sectoral synthesis, highlighting shared challenges and opportunities across disciplines and lifecycle stages. It identifies the functional roles, enabling technologies and systemic barriers affecting digital platform adoption, such as fragmented data sources, limited interoperability between systems and siloed organizational processes. These barriers hinder the development of integrated and adaptive digital ecosystems capable of supporting real-time decision-making, participatory planning and sustainable infrastructure management. The study advocates for modular, human-centered platforms underpinned by standardized ontologies, explainable AI and participatory governance models. It also highlights the importance of emerging technologies, including large language models and federated learning, as well as context-specific platform strategies, especially for applications in the Global South.

Keywords: cross-sectoral integration; Building Information Modeling (BIM); digital twin; Artificial Intelligence (AI); lifecycle cost management; BIM-GIS integration; participatory governance; sustainable infrastructure

1. Introduction

The Architecture, Engineering and Construction (AEC) sector is undergoing a digital transformation, driven by the convergence of cross-cutting technologies such as Building



Academic Editor: Pablo Pujadas Álvarez

Received: 5 June 2025

Revised: 4 July 2025

Accepted: 8 July 2025

Published: 10 July 2025

Citation: Berlato, M.; Binni, L.; Durmus, D.; Gatto, C.; Giusti, L.; Massari, A.; Toldo, B.M.; Cascone, S.; Mirarchi, C. Digital Platforms for the Built Environment: A Systematic Review Across Sectors and Scales. *Buildings* **2025**, *15*, 2432. <https://doi.org/10.3390/buildings15142432>

Copyright: © 2025 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license

(<https://creativecommons.org/licenses/by/4.0/>).

Information Modeling (BIM), artificial intelligence (AI), the Internet of Things (IoT), Digital Twins (DTs), blockchain and cloud-based collaborative platforms [1]. Over the past two decades, BIM has laid the groundwork for this transition by enabling integrated data environments that enhance coordination across design, construction and facility operations [2]. Today, the sector is entering a more complex and integrated phase, in which these technologies not only support real-time monitoring, predictive analysis and lifecycle asset management but also challenge traditional organizational and governance models [3]. However, critical gaps persist, particularly during the construction stage, where integrated platforms for real-time coordination and data exchange remain limited and process fragmentation continues to hinder seamless digitalization.

In spite of these advancements, the AEC sector remains faced with long-standing difficulties that prevent full digitalization [4]. These challenges run deep into the intrinsic characteristics of construction products that are immobile and unique, heavily customized and with long life cycles. Also, the sector remains highly fragmented, involving mainly micro and small-sized companies and dominated by public sector actors, particularly in the context of infrastructure development. In addition to these challenges, the sector needs to address the increased demands toward sustainability and social responsibility such as decreasing the energy consumption and greenhouse gas emissions, improving the resilience and interconnectivity of building and infrastructure systems, ensuring fair access to housing, eliminating the need for resources and the waste generation, and the promotion of circular economy models [5].

These complex challenges require a paradigm shift toward more systemic, integrated and participatory methods of managing data, processes and stakeholders during the whole lifecycle of constructed assets. Digitalization theoretically guarantees the improvement of productivity, sustainability and resilience, but it is preceded by a contradictory scenario, as revealed by Zhang et al. [6] and Asif et al. [7]. The AEC sector still shows stagnating and even decreasing productivity and low levels of digital technology adoption among small and medium-sized enterprises (SMEs). The most significant difficulties are the limited accessibility of usable, reliable and structured information for decision-making; the uncertainty of construction site operations due to changing variables and fragmented workflows; the inherent complexity involved in construction projects; and the challenges of cost estimation, lifecycle analysis and risk management.

Though BIM has shown positive contributions toward the solution of these problems, substantive barriers remain in the capacity of its support for seamless multi-scalar and cross-organization data integration and knowledge reuse [8]. The construction industry still lacks effective mechanisms for the generation, coordination and utilization of data and information cooperatively across the project phases, the organizational boundaries, and the territorial scales [9,10]. This deficiency hinders the development of resilient and agile knowledge bases that are essential for informed decision-making and performance optimization in complex and uncertain environments.

In this context, digital platforms, defined here as modular, interoperable systems that integrate data and workflows across stakeholders, emerge as potential drivers of transformative change within the AEC sector with the potential to offer inclusive, interoperable and modular environments for the coordination of data, information, knowledge bases and processes across technologies, stakeholders, project phases and scales [11]. The concept of digital platforms is intrinsically wide and multidimensional, spanning across technology, product, domain and governance aspects and involving a broad array of functionalities ranging from data integration and visualization into decision support, lifecycle management, participatory planning and collaborative governance [12].

Beyond their technical capacity, digital platforms are conceived as socio-organizational facilitators, enabling more effective communication, stakeholder alignment and cross-institutional collaboration. Their role as orchestrators of procedural and institutional transformation may represent their value in the AEC sector, where fragmented actors and siloed decision-making often impede innovation and systems integration.

Recent academic and industrial efforts have started investigating the development and application of digital platforms in the AEC sector, but these efforts remain fragmented and typically concentrate on a particular technology (like BIM or DT platforms), a certain domain (like energy management or asset maintenance) or a specific phase of a building's life cycle (like the design phase, the construction phase or the operational phase) [13]. While digital platforms often incorporate technologies like digital twins and AI, they differ in that platforms provide the infrastructural backbone and governance architecture through which these technologies interoperate, scale and deliver user-facing services.

While these research initiatives reflect a vision aligned with emerging European digital frameworks such as DigiPLACE and GAIA-X, the practical application of such platforms in the construction industry and public administration remains limited [14]. Digital maturity across the sector is uneven, and many proposed solutions are still at the conceptual or prototype stage. As a result, there is a disconnect between the systemic integration envisaged in academic discourse and the current technological readiness and adoption capacity of most industry actors, particularly SMEs and local administrations [15].

The existing body of literature lacks a systemic and cross-sectoral synthesis of how digital platforms can act as orchestrators of digital transformation. Only a limited number of studies compare platform use across sectors or life cycle stages; most instead concentrate on isolated domains, technologies or phases. This reinforces the need for a broader review that examines digital platforms as socio-technical ecosystems: not only technological tools, but also enablers of organizational data governance and collaborative workflows [16]. The current fragmentation of research across technological domains and sectoral applications limits the ability to develop shared frameworks, data standards and governance models. This constrains not only knowledge transfer but also the practical integration of digital platforms across construction, infrastructure and energy systems [17]. For example, while AI applications in risk management and safety monitoring are emerging within the AEC sector (e.g., real-time hazard detection and predictive maintenance using computer vision and machine learning), their integration into comprehensive, interoperable platform ecosystems remains limited due to sectoral silos [18].

Therefore, this paper recognizes that the current state of the field reflects both innovative potential and a lack of operational readiness. It aims to provide a critical mapping of this landscape, highlighting not only technological possibilities but also the socio-institutional gaps that need to be addressed to enable adoption and impact.

This paper bridges this research gap by providing a systematic and cross-sectoral literature review of digital platforms in the built environment and associated domains. In doing so, it addresses a diverse audience that includes not only AEC researchers but also urban planners and public policy designers engaged in the digitalization of cities and services. By adopting a multi-domain and multi-scalar perspective, the paper contributes to the existing body of knowledge by investigating how digital platforms might develop from technical tools into interoperable governance infrastructures, bringing together technical and institutional aspects across lifecycle stages and spatial scales. The timeliness and relevance of advancing research and development in this area are supported by the current European and international efforts toward promoting digital platforms and industrial data spaces. Some examples include the European DigiPLACE project, which aimed at establishing a reference architecture framework for the next-generation digital platforms for

the construction sector; the French Kroqui platform; and broader cross-sectoral projects, like GAIA-X, that aim to create a federated and trustworthy data-sharing environment. Even with these encouraging developments, however, scientific knowledge is still fragmented and lacks a critical and coherent comprehension of the roles, challenges and potential paths of digital platforms in the AEC sector and the built environment at large.

By addressing this gap, the present paper contributes both to scientific and practical awareness by establishing an extensive and critical state-of-the-art review that synthesizes a systemic understanding of digital platforms as socio-technical ecosystems with the potential of creating more integrated, participatory and sustainable built environments. The paper is intended to guide researchers, practitioners and policymakers in rethinking the design, development and governance of next-generation digital platforms with a focus on ensuring that they become facilitators of systemic innovation and address the pressing sustainability, efficiency and inclusive challenges facing the built environment.

Accordingly, the paper is organized as follows. The methodology section describes the research design and systematic literature review protocol. The subsequent chapters offer six thematic domains of analysis according to the following topics: artificial intelligence in digital platforms, digital twin-enabled platform integration across domains, lifecycle cost management using platforms, BIM-GIS-based platform integration for underground utility infrastructure systems, platform-based solutions in the energy sector, and public administration and governance digital platforms. The discussion section presents a cross-domain synthesis of the outcomes, limits, and future trends of digital platforms with a critical outline of the directions for future research. Lastly, the conclusion section presents the most significant findings and discusses the limitations of the study.

2. Methodology

This review was conducted in accordance with the PRISMA 2020 guidelines [19]. A PRISMA flow diagram illustrating the search and selection process is included in the Supplementary Materials. Although no formal protocol was registered in a prospective database, such as PROSPERO, the decision to adopt a systematic review approach was justified by the need to synthesize fragmented and dispersed literature on digital platforms in the built environment. Given the increasing academic and policy interest in platform-based digital transformation and the absence of existing cross-sectoral reviews, this approach was deemed to ensure transparency and thematic coherence.

The choice to adopt a systematic approach was a response to the fragmented and interdisciplinary nature of digital platform research across the built environment, ensuring that the outcomes are both reliable and transferable across the sectors examined. Through the inclusion of thematic review methodology, this research also aimed to synthesize not only technological innovations but also the socio-technical and governance dimensions that increasingly characterize the role of digital platforms.

At the outset of the review process, the authors developed a definition of digital platforms that is both sectoral and consistent across sectors. Digital platforms are socio-technical ecosystems that orchestrate data, technologies, actors and services to enable multi-scalar, cross-sectoral collaboration and decision-making. While they may integrate enabling technologies such as digital twins, BIM, and IoT, platforms are distinguished by their role in hosting, coordinating and scaling these technologies into cohesive service environments, rather than functioning as standalone tools. Specific focus is given to the dual role of platforms as both technological infrastructures and socio-organizational facilitators enabling technical tasks such as monitoring, simulation and optimization, as well as broader managerial and institutional activities, including decision support, participatory planning, regulation and compliance, and governance innovation. This framework

recognizes the multidisciplinary nature of digital platforms that embed technologies such as artificial intelligence, digital twins, Building Information Modeling, Geographic Information Systems, Internet of Things, and blockchain that operate at scales from individual building design and construction to urban system and infrastructure management and governance, as well as even regional or national assets. As shown in Figure 1, digital platforms can, therefore, be conceptualized as orchestrators that integrate and harmonize data repositories, advanced technologies, various stakeholders and business processes.

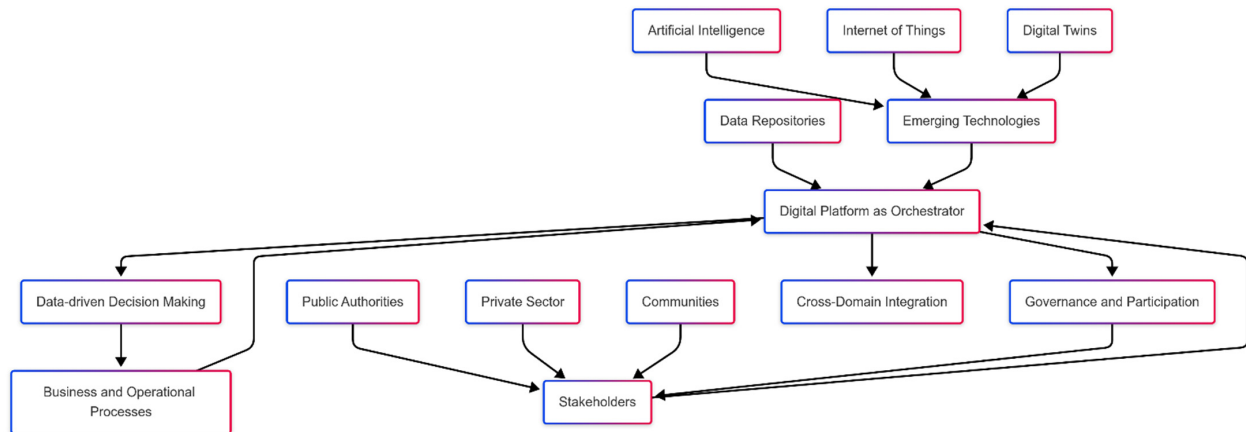


Figure 1. Conceptual framework illustrating the role of digital platforms as orchestrators of data, stakeholders, technologies and processes within the built environment.

To enable a systematic comparison of digital platform deployments across their uses, functionalities and challenges, this paper presents a concept-driven framework structured along four key analytical dimensions: the domain of application, the functional purpose, the technological integration and the lifecycle phase or spatial scale. Displayed in Table 1, this framework aimed to enable a structured, multi-dimensional and cross-comparable examination of digital platform implementations and identify sectoral uses, as well as reveal cross-cutting technologies and governance models. The framework served as a necessary tool for combining information across diverse domains, such as construction, infrastructure management, energy, urban planning and public administration with their own specific terminologies, stakeholders and regulations.

Table 1. Conceptual framework for the analysis of digital platforms.

Dimension	Examples
Domain of application	Construction, Infrastructure, Energy, Urban Planning, Public Administration
Functional purpose	Monitoring, Decision Support, Cost Estimation, Participatory Planning, Maintenance
Technological integration	AI, Digital Twin, BIM, GIS, IoT, Blockchain, AR/VR
Lifecycle phase or scale	Design, Construction, Operation, End-of-Life; Building, Urban, Regional Scales

The Scopus database was employed to conduct the literature review because of its comprehensive and multidisciplinary coverage of peer-reviewed articles across engineering, environmental sciences, computer science, and public administration. For each of the six thematic domains selected—artificial intelligence in the construction process, digital twin integration, lifecycle cost management, BIM-GIS integration for underground utility infrastructure, energy sector platforms, and public governance and administration platforms—a

series of specific Boolean search terms was formulated. These combined generic terms descriptive of digital platforms, i.e., “digital platform,” “data space” and “information container,” with terms describing the technology and the specific domain of the technology, such as “construction,” “cost management,” “energy,” “public governance,” “underground utility infrastructure,” “artificial intelligence,” “machine learning,” “digital twin,” “BIM” and “GIS.” The iterative and exploratory nature of the search terms enabled the process of refining them to ensure topic applicability, thereby excluding irrelevant outcomes and achieving a sample of pertinent studies.

The search for articles was restricted to English-language journal publications between 2015 and early 2025. This date range was chosen to reflect the recent surge in platform-centric research and technological integration across the AEC and urban governance sectors. Specifically, 2015 marks an inflection point, corresponding with increased scholarly attention and the launch of major digitalization initiatives such as the European Commission’s DigiPLACE and the early conceptualization of cross-sector data spaces. The timeframe thus captures a decade in which platform strategies became central to digital transformation efforts.

Following the literature search, a rigorous, transparent three-step screening procedure was used to ensure thematic consistency and conceptual coherence throughout the considered domains. The initial phase encompassed document type and language filtering to rule out works that were not peer-reviewed and publications that were not written in English, ensuring the scholarly rigor of the selected literature. In the second phase, the titles and abstracts of the remaining records were screened in order to assess whether they align with the study’s focus on digital platforms as integrators of technologies, decision support enablers or orchestrators of lifecycle optimization processes. This phase ensured that the platform is positioned at the center of the process of technological integration, decision-making or data-driven innovation. The third and last stage involved a full-text examination of the shortlisted articles in order to ensure their relevance and that the digital platform lay at the center of the discussed technological, organizational or institutional process. To double-check the thematic completeness of the sample and discover any other suitable studies that had not emerged using the keyword search alone, backward and forward reference checking was conducted. Additional relevant articles were incorporated based on the domain expertise of the authors, ensuring the inclusion of seminal studies and those that addressed emerging research directions. The selection process as a whole, from search outcomes, screening phase and final inclusions, is laid out in Table 2.

Table 2. Core set of articles, distributed across six thematic areas.

Platform Domain	Initial Results	Abstract Screen	Full-Text Review	Final Inclusion
AI	794	23	21	21
Digital Twins	401	36	21	21
Lifecycle Cost Management	61	28	17	17
BIM-GIS for UIs	454	34	21 (+1 added)	22
Energy Sector	240	33	28 (+2 added)	30
Public Administration	111	19	13 (+1 added)	14
Total				125

Each of the 125 selected articles was subjected to a structured process of data extraction. This included the systematic recording of key details, such as publication information, objectives of the research, methods used, principal outcomes, technologies addressed, platform features and the specific domains and lifecycle phases they focused on. Articles were then categorized within the six macro-domains and further annotated with such specific

thematic topics as predictive analytics, lifecycle optimization, participatory planning or governance models. This strict classification enabled both in-depth analysis within each of the domains, as well as an across-domains synthesis that was essential for the identification of technological integration patterns and shared limitations and systemic barriers, as well as emerging opportunities for research that cut across sectors.

The choice of using a cross-domain comparison strategy is central to the study's methodological approach. Given the fragmented nature of the literature on digital platforms—seldom confined within sectors such as construction, energy or public administration—this study employed an integrative methodology to identify cohesions, shared issues and systemic constraints that exceed specific sectors. This approach allows for the recognition of digital platforms as socio-technical infrastructure that mediates and orchestrates data, process and stakeholder interactions across scales, sectors and governance contexts. By systematically comparing six diverse thematic domains, this study aimed to show both sectoral attributes and cross-cutting dynamics that reveal the current digital platform landscape's structural immaturity, interoperability problems and governance issues. Therefore, the cross-domain synthesis is not an analytical exercise but a qualitative methodological decision aimed at revealing the existing research gaps, emerging interdisciplinary trends and possibilities of more integrated, participatory and sustainable platform ecosystems.

In spite of providing a robust and structured synthesis of scholarly literature, the authors acknowledge some methodological constraints. The exclusive reliance on the Scopus database, as justified for its comprehensiveness, may have left out pertinent studies indexed in other databases, such as Web of Science, or contained within grey literature such as technical reports, standards and white papers that often capture seminal practice-oriented insights or early-stage innovations. Excluding conference papers and book chapters might have further restricted the inclusion of emerging conceptual models and pilot projects that have not yet emerged into journal publication.

While this study offers a comprehensive synthesis of peer-reviewed academic literature, one notable limitation is its reliance on English-language sources. This introduces a potential geographic and cultural bias, as most indexed literature originates from institutions and researchers in the Global North. However, the challenges and patterns that emerge, such as data fragmentation, platform immaturity, interoperability issues and institutional inertia, are often systemic and not exclusive to the Global North. As such, they may offer valuable reference points for identifying analogous barriers and guiding digital platform development in Global South contexts, provided that they are adapted through context-sensitive implementation strategies.

Future research could address this by including academic and grey literature published in other languages, such as Italian, Spanish, French, or Chinese, to better represent Southern European, Latin American, and Asian perspectives on digital platform development in the built environment. This constraint underlines the need for follow-up research into digital platform development and deployment in the Global South, where there might be differences in socio-institutional conditions, technological adoption pathways, and governance concerns. While these constraints follow from the scope of the study and methodological rigor, they open up possibilities for such subsequent studies as empirical case-study research, stakeholder workshop sessions and policy conversations that might corroborate, contextualize and augment the evidence of the current study to make it generalizable across various global contexts. Accordingly, while the review's findings may not be generalized to all geographical regions, especially those underrepresented in English-language academic discourse, they provide a framework upon which tailored studies can be developed. Future research should aim to include primary case studies and

literature from underrepresented regions to validate and adapt the proposed conceptual models and cross-domain insights in diverse local conditions.

As this review did not involve meta-analytical synthesis or statistical comparison of study outcomes, no formal risk of bias assessment was conducted. The included studies were instead evaluated qualitatively based on their thematic relevance and methodological transparency. Likewise, no standardized effect measures (e.g., risk ratios, mean differences) were applied, given the descriptive and cross-sectoral nature of the synthesis.

3. Thematic Domains Analysis

3.1. Artificial Intelligence in Digital Platforms

The construction industry has recently started to integrate AI into digital platforms to increase efficiency, reduce costs and improve project management. AI-enabled digital platforms refer to socio-technical systems where AI acts as a major operational component shaping decision-making, automation and real-time optimization rather than serving as a peripheral feature [20,21]. These platforms benefit from AI capabilities such as machine learning, deep learning, neural networks and predictive analysis to provide dynamic interaction between stakeholders and systems, supporting complex processes such as design, project management and life cycle assessment in the construction industry (Figure 2).

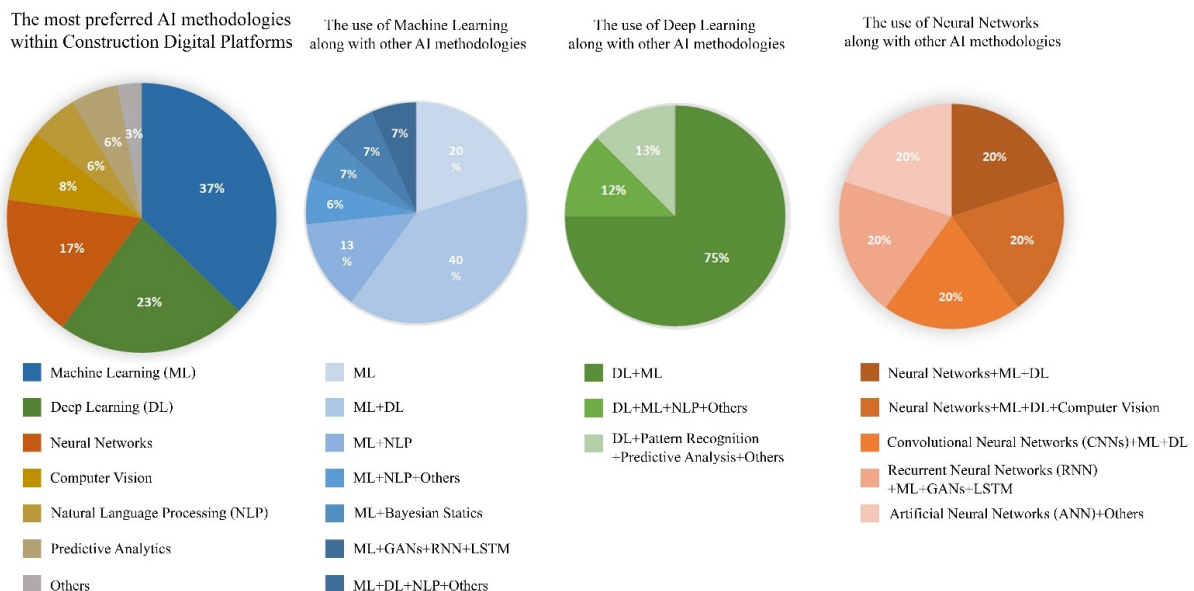


Figure 2. The use of AI methodologies within digital platforms.

Digital platforms in the construction industry usually integrate technologies like BIM and digital twins to optimize workflows [22]. However, persistent challenges such as project delays, security concerns, communication gaps and lack of interoperability between digital tools make the progress of construction projects difficult [23]. Traditional project management approaches struggle to handle the complexity of modern construction, making advanced technological interventions necessary.

Recent research suggests that AI has the potential to help address these challenges by enabling predictive analytics, real-time decision-making and automation, although widespread implementation remains limited. For instance, AI-based tools have been applied to construction risk management by improving safety protocols, optimizing resource allocation and supporting proactive hazard detection through computer vision and deep learning models [24]. In particular, real-world applications such as real-time safety monitoring systems using AI-powered computer vision have shown promise in detecting

unsafe conditions on construction sites, thereby reducing the risk of accidents [25]. Similarly, AI-powered digital twins are being explored for real-time monitoring and adaptive planning in large-scale construction projects, aiming to reduce uncertainties and improve responsiveness to dynamic conditions [26].

AI is also being explored for its role in automated design processes, where machine learning techniques are used to optimize structural integrity, material efficiency and cost-effectiveness [23]. In waste management, AI-enabled platforms contribute to circular economy principles by reducing material waste and enhancing sustainability practices [23]. Safety solutions powered by AI offer dynamic risk assessment through real-time monitoring, enabling the early detection of potential hazards and improving workplace safety outcomes [24]. Moreover, AI contributes to cybersecurity in construction platforms by enhancing the protection of sensitive project data from cyber threats [26].

While many of these applications also have relevance in other domains such as energy and manufacturing, their implementation within the AEC sector is being tested in research and pilot projects. For instance, AI-supported mobility prediction and optimization solutions are being adapted to improve construction site logistics and workforce scheduling [27].

Overall, these technological advancements suggest that AI has the potential to enhance efficiency, safety and sustainability in construction, but further empirical validation and sector-specific adaptation are needed to fully realize these benefits.

3.1.1. AI-Integrated Digital Platforms for Improved Construction Safety and Efficiency

The integration of AI into digital construction platforms is significantly improving efficiency, safety and cost-effectiveness. Among the methodologies adopted, machine learning and deep learning algorithms develop cost estimation and risk assessment [26]. AI-powered predictive analytics help stakeholders optimize project management by anticipating delays, refining schedules and allocating resources more efficiently [24].

One of the most significant AI advantages found in the literature is its impact on safety and risk management. AI-driven computer vision and deep learning models support real-time monitoring of construction sites, identifying potential hazards and preventing accidents [24]. This proactive approach minimizes human error and ensures compliance with safety regulations. Similarly, AI-powered digital twins provide real-time monitoring and adaptive planning, reducing uncertainties in large-scale projects. Additionally, AI-driven cybersecurity measures protect sensitive construction data from cyber threats, ensuring data integrity and preventing unauthorized access [26].

3.1.2. Improved Sustainability and Resource Efficiency Through AI

Beyond efficiency and safety, AI contributes to sustainability through digital platforms by supporting circular economy principles. AI-integrated digital platforms optimize material usage and reduce waste in construction projects [23]. AI-powered solutions such as the PLUG-N-HARVEST platform improve energy efficiency in smart buildings, contributing to environmental sustainability [28]. Furthermore, AI provides collaboration among stakeholders by simplifying workflows and improving communication within digital platforms [28].

The integration of AI, especially machine learning, into platforms such as City Intelligent Modelling (CIM) improves data analysis and decision-making capabilities, leading to increased efficiency and sustainability in the reconstruction and management of historical buildings [29].

Analysis using algorithms and monitoring techniques on AI-integrated platforms minimizes construction waste, optimizes energy use and promotes recycling [22]. AI-

powered design-stage technologies enhance lifecycle assessment and reduce unnecessary material consumption [23]. Another example of the integration of AI-driven methodologies within the MInt platform aims to enhance the efficiency of materials development by systematically predicting optimal processing conditions and material properties [30]. By utilizing Bayesian optimization and surrogate modeling, Demura [30] seeks to minimize waste through targeted experimentation and computation, thereby promoting sustainable practices in materials engineering. This approach not only allows for more efficient use of resources but also supports the design of materials that meet performance requirements while reducing environmental impact. Moreover, AI-supported agricultural-infrastructure planning supports sustainable land use in urban expansion [31]. Deep-learning techniques provide dynamic monitoring and control of environmental emissions in hybrid-energy process plants, which improves compliance with emissions regulations and process efficiency [32].

3.1.3. AI-Integrated Platforms for Smart Urbanism, Collaboration and Innovation

The research shows that AI-enabled platforms also promote urban infrastructure optimization, improving energy efficiency and governance through predictive analytics and real-time monitoring [33]. AI also supports social democratization, helping city administrators analyze urban complaints and make informed decisions [34,35]. He [36] emphasized that AI technologies such as generative adversarial networks (GANs) and clustering algorithms empower urban planners and architects to collaboratively engage with large datasets, leading to innovative design solutions and smarter urban environments that better meet the needs of society and emerging urban dynamics [36]. Furthermore, the integration of deep learning techniques, particularly through the use of Google Teachable Machine, offers significant benefits in the recognition and classification of cultural heritage sites, enhancing the efficiency and accessibility of digital preservation efforts [37].

The integration of machine learning algorithms into digital platforms for flexible on-demand mobility services increases operational efficiency by accurately predicting travel-demand patterns and optimizing infrastructure management, ultimately providing users with faster and more convenient transportation options [38]. A hybrid model employing stacked regression with social media traces from Flickr improves the prediction of human-mobility flows across spatial scales, thereby supporting urban planning and resource allocation [39].

As another benefit, the Metaverse, as a virtual model of platform urbanism, explores how AI and digital platforms contribute to urban planning simulations [21]. On the other hand, the literature notes that the use of AI in metaverse-based construction design raises legal and regulatory concerns, while high computational costs restrict participation [40]. In the industrial domain, AI adoption in Industry 4.0 has led to automated workflows, improved robotics and optimized supply-chain management. AI-driven industrial platforms facilitate iterative product innovation, enhance material selection and reduce construction costs [20]. Furthermore, AI-powered predictive maintenance and equipment tracking maximize operational efficiency [21].

As AI evolves, its integration into digital construction and urban platforms will drive further innovation. Continued research and investment in AI technologies will contribute to a smarter, safer and more sustainable construction sector, ensuring long-term resilience and efficiency.

3.2. Digital Twin Integration Through Digital Platforms

DTs serve as enabling technologies that synchronize digital replicas with real-time physical data, enhancing monitoring and simulation capabilities. When embedded within

digital platforms, DTs contribute to broader system orchestration by feeding real-time data into platform services for planning, decision support and lifecycle optimization.

The Industrial Digital Twin Association (IDTA) defines a digital twin as “a virtual representation of real-world entities and processes, synchronized with specified frequency and fidelity” [41,42]. In the context of Industry 4.0, the integration of DTs with digital platforms (DPs) helps communication and interoperability between different systems [43,44]. Digital platforms facilitate data exchange, analysis and decision-making, enhancing the effectiveness of DT applications. The Internet of Twins (IoTw) enables disaggregated DTs within a distributed cloud architecture, optimizing fidelity and synchronization [45]. Additionally, the concept of Data Spaces, federated data ecosystems, facilitates secure and standardized data sharing across industrial environments, fostering innovation, sustainability and operational efficiency [42].

This section explores the application of digital platforms for DTs across structures and infrastructures, smart cities, cultural heritage and energy efficiency (Figure 3). Integrating DT-DP technology enhances real-time monitoring, predictive analytics and automation, leading to more robust and intelligent systems.

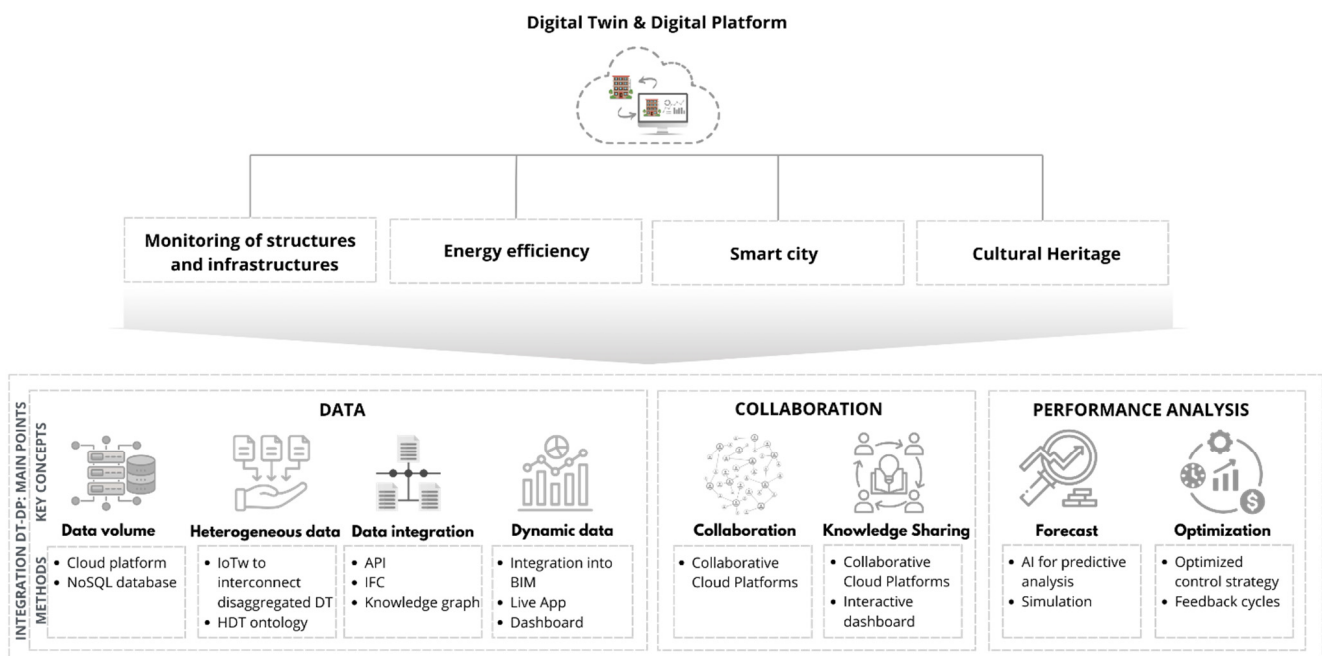


Figure 3. Application of digital platforms for digital twins: main points.

3.2.1. Monitoring of Structures and Infrastructures

Bridging the gap between physical assets and their digital counterparts using digital twins and digital platforms is crucial for improving infrastructure management and driving digital transformation forward. Various studies emphasize that a digital platform is key to centralizing, processing and transforming data, which, in turn, boosts our ability to monitor and maintain infrastructure effectively [46,47]. Cloud platforms provide the necessary infrastructure for managing the vast amount of heterogeneous data generated by sensors and BIM systems [46]. The adoption of DTs in infrastructures such as bridges, airports and metropolitan tunnels requires seamless interoperability between existing and emerging systems. Fawad et al. [48] emphasized the importance of integrating Structural Health Monitoring (SHM) systems with BIM-based web platforms to automate bridge management, enabling bidirectional data exchange and optimizing asset performance. Similarly, Keskin et al. [49] propose a modular DT architecture for airports, addressing operational inefficiencies and fostering a scalable, interconnected digital ecosystem. A common aspect

of the studies is the need for advanced data management to support reliable decision-making. Li et al. [50] proposed a DT-IOM platform for the management and maintenance of steel hydraulic structures, emphasizing the role of IoT connectivity, modeling and 2D/3D visualization in improving operational efficiency. Rodríguez-Alonso et al. [47] highlighted the use of microservices architectures to ensure flexibility, scalability and interoperability between digital systems, facilitating infrastructure control through intuitive user interfaces and advanced analytics. Zhou et al. [51] proposed a DT platform for the management of metropolitan tunnels, highlighting the importance of real-time data collection, early warning systems and predictive maintenance. The implementation of DTs in these contexts is supported by advanced technical frameworks that combine geometric models, data analysis, and AI simulations to optimize the management of infrastructure assets.

3.2.2. Smart City

Interfacing digital twins with platforms is crucial for ensuring the monitoring, management and simulation of complex urban environments. A central aspect of this integration is the ability to collect, process and visualize real-time data, creating a dynamic representation of urban spaces. As highlighted by Dani et al. [52], a DT-based digital platform is crucial for monitoring and simulating urban conditions, providing an advanced decision-support system. The integration of data from IoT sensors, CCTV cameras, and geographic information allows for the creation of detailed city models, improving forecasting capabilities and urban resource management. The importance of this integration is also evident in environmental monitoring. Cho et al. [53] demonstrated how a digital platform can facilitate the collection and management of environmental data through an Android application. Additionally, Lee et al. [54] emphasized that a geospatial platform integrated with an urban DT is a prerequisite for effective management of large-scale individual mobility. The collection of dynamic data on pedestrians and vehicles, real-time updates of urban models, and the use of data compression technologies highlight the crucial role of digital platforms in making the digital twin an evolving representation of reality. This concept is further developed by Yang and Kim [55], who conceptualized the Urban Digital Twin as a virtual platform that reflects and interconnects the various systems of a city, enabling the resolution of complex urban issues through simulations and stakeholder participation.

3.2.3. Cultural Heritage

Integrating DT and DP underpins the capability to manage cultural and urban heritage. Studies highlight the importance of integrating data from different sources: on one hand, the use of a knowledge base and ontology for managing cultural heritage knowledge [56] and, on the other, the integration of structural and participatory data [57]. Interoperability is a key enabler for system integration and streamlined data access. The articles recognize the role of digital platforms in supporting informed and participatory decision-making. The digital platform also aids in proactive management and promotes citizen participation in heritage regeneration.

3.2.4. Energy Efficiency

Digital twin-based platforms integrate DTs with other technologies such as BIM and IoT to create interoperable environments for real-time monitoring and urban system management. In this context, the platform acts as the coordination layer, enabling multi-user access, data governance and cross-system interaction based on DT inputs.

In the context of energy monitoring, the integration of digital twins with digital platforms enables intelligent control of heating, ventilation, air conditioning (HVAC) and lighting systems based on occupant presence, thereby improving energy efficiency [58]. Digital platforms can use predictive and machine learning algorithms to analyze data and

predict the future behavior of systems and resources, optimizing energy consumption and maintenance. For example, in energy monitoring, data from HVAC systems, lighting and heating systems are analyzed to identify inefficiencies and reduce operating costs [59]. In addition, the integration of BIM models and 3D simulations enables the visualization of data, making it more understandable to non-experts and facilitating more intuitive building management. Interactive dashboards allow for remote facility management, reducing the need for manual intervention and improving operational efficiency [60,61]. Digital platforms can make the adjustment of parameters such as ventilation and lighting automatic, optimizing management and reducing energy consumption. In addition, predictive management of equipment, such as maintenance based on real-time and historical data, helps prevent failures and improve system reliability. The combination of various technologies, such as IoT, BIM and environmental sensors, enables efficient and intelligent building management, as seen in air quality monitoring [62].

The integration of digital twins and digital platforms is transforming the way we model, monitor, and manage complex physical systems. From infrastructures to cultural heritage, and from energy management to smart cities, this synergy enhances real-time responsiveness and predictive capabilities. However, future efforts must focus on improving semantic interoperability, data sovereignty and inclusivity to ensure that these technologies contribute to sustainable and equitable digital transformation.

3.3. Digital Platforms for Lifecycle Cost Management

Cost management in construction projects is a critical aspect that goes beyond the execution phase, encompassing the entire project lifecycle [63]. While cost estimation mainly focuses on the execution stage, where forecast accuracy is key to project success [64], cost management includes broader dimensions, such as design phase planning, economic feasibility, facility operation costs and unforeseen expenses, like delays, legal fees and design changes. In this context, digital platforms play a pivotal role by enabling integrated and transparent cost oversight. They support more effective planning and precise risk management. The following section explores how digital platforms can positively impact cost management, both directly and indirectly, focusing on three main aspects: data integration across domains, information traceability and transparency, and process optimization, as summarized in Figure 4.

3.3.1. Data Integration Across Domains

A major challenge in cost data integration is the fragmentation of information across various sources and formats [65]. Integrated data management in digital platforms for cost management is addressed in various studies. Li et al. [66] improved cost control in the prefabricated component supply chain by integrating cost and scheduling data with real-time information on location, design specifications and production status using IoT and BIM. This system optimizes logistics and reduces operational costs by minimizing delays and assembly errors. Wang et al. [67] proposed a platform that centralizes BIM, technical, economic, scheduling, workforce, material and equipment data, incorporating inputs from laser scanners, IoT sensors and video. The platform enables cost control by comparing planned and actual data, showing a 65% improvement in efficiency, a 30% reduction in time, 27% less labor, and a 39% increase in productivity. Lv et al. [68] presented a platform for road infrastructure design and management that integrates BIM and GIS with advanced 3D visualizations. It optimizes road alignment design, enhancing decision-making accuracy and reducing design time and costs. For instance, in a pilot deployment within a mid-sized municipality, the implementation of a BIM-integrated cost management platform led to a 25% reduction in project cost overruns and shortened procurement timelines by 30% [69].

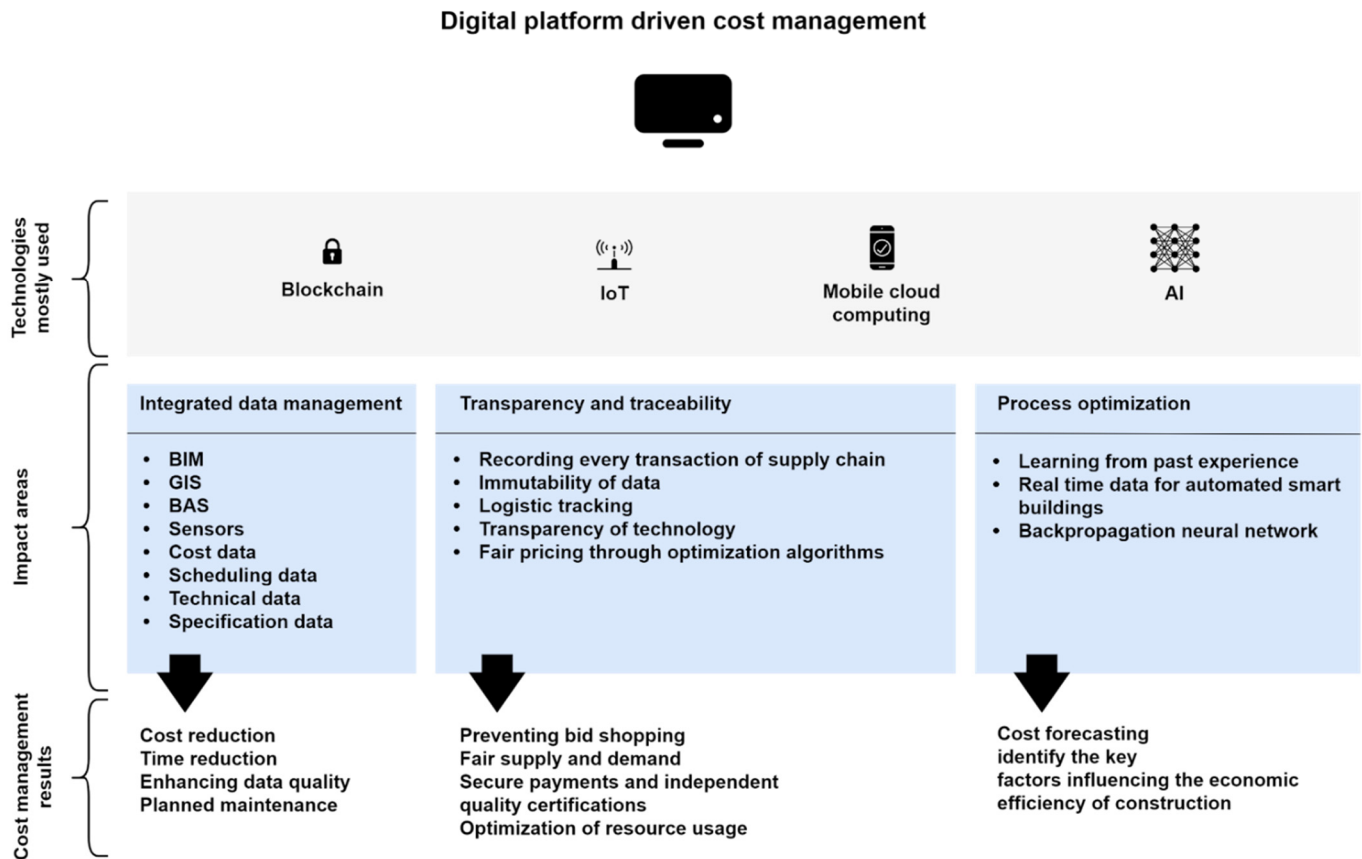


Figure 4. Comprehensive view of technologies used in digital platforms for cost management and the main impact areas with related results.

Moreover, Hagedorn, Pawels et al. [68] proposed an architecture to ensure data consistency across heterogeneous sources, enabling automated information validation. Building on this, Hagedorn, Liu, et al. [70] developed a platform for infrastructure lifecycle management, where data are continuously monitored and validated across all asset lifecycle domains. These two works lay the foundation for reliable lifecycle cost analysis based on consistent datasets and support the implementation of predictive maintenance strategies, a theme directly addressed by Katipamula et al. [71]. The study analysed open-source platforms for condition-based continuous maintenance, integrated with BIM and Building Automation Systems (BASs). These solutions enable the real-time identification of inefficiencies and fault prevention. They also support energy-saving strategies, optimizing resources and ensuring more effective building management, yielding substantial operational savings and prolonged asset lifespans.

3.3.2. Transparency and Traceability

Digital platforms also address another key aspect, namely the possibility to enhance transparency and traceability in project management. In recent years, there has been an increase in the use of blockchain for developing decentralized platforms. For instance, Li et al. [72] combined blockchain with IoT to record every transaction in the supply chain of prefabricated modules, ensuring the verifiability and immutability of data such as BIM model modifications and logistics tracking. This integration not only optimizes resource usage and reduces costs but also increases trust among stakeholders. Similarly, Stas and Abrishami [73] enhanced cost management by combining blockchain and Work Breakdown Structure (WBS) by enabling the real-time tracking of financial transactions and contract execution via smart contracts, while WBS minimizes cost overruns through detailed tasks

and budget breakdowns. Yu and Sun [74] further support the transparency of prefabricated green technologies' costs and the performance of stakeholders facilitating accessible information sharing among stakeholders. The implementation costs of sustainable technologies (such as the use of eco-friendly materials or low-emission processes) are tracked and made available across the supply chain. This visibility enables prefabricated component manufacturers and contractors to clearly understand the actual costs of adopting green innovations. As a result, it supports more informed decisions regarding sustainable solutions, facilitates the comparison of different cost–benefit strategies and strengthens stakeholder accountability.

Turning to the issue of bidding fairness, two studies addressed this aspect, with a focus on cost transparency. Yang and Zhong [75] proposed a platform that balances supply and demand by addressing information asymmetry and promoting fair pricing through optimization algorithms. The system ensures transparency by preventing unfair practices like bid shopping and incorporates customization based on user and service provider preferences for a fair distribution of opportunities. In addition, Hu et al. [76] presented a platform in the architectural design sector that optimizes resource management by connecting design firms with a broader pool of professionals through an intelligent matching system, bypassing limited traditional intermediaries. Transparency is maintained through secure payments and independent quality certifications.

3.3.3. Data Driven Process Optimization Through Automation

The final section examines how platforms, through a general process of optimization, have a positive impact on cost management. Wu [77] integrates the use of BP Neural Network and Genetic Algorithms for real-time monitoring and cost forecasting, reducing estimation errors to 1.77% and the average cost compared with the baseline of 78.68%. An alternative approach leverages distributed location sensing, which collects real-time data through IoT sensors and vision systems to enhance automation and energy management in buildings, reducing operational costs and resource waste and improving occupant comfort [78]. Concerning the design and the construction phase, Mishchenko et al. [79] proposed a framework for developing an organizational and technological platform aimed at optimizing monolithic construction with pneumatic formwork. The study employed a hierarchical decomposition method of building processes to identify the key factors influencing the economic efficiency of construction, allowing the implementation of strategies for optimizing costs. The platform, which is still under development, described by Wu and Shih [80], supports architectural design by introducing a visual real-time cost visualization interactive dashboard, aiming to overcome traditional workflows where cost estimations and technical analyses come too late for strategic decisions.

Núñez et al. [81] adopted an alternative approach based on mobile cloud computing for optimizing the resource management process. The platform was designed to enhance knowledge management in SMEs within the Chilean construction sector, facilitating the collection and sharing of “lessons learned” in projects. The platform reduces economic and technical barriers, improves real-time collaboration and optimizes resource management.

Digital platforms are transforming cost management in construction by enhancing data integration, transparency and process optimization across the entire project lifecycle. Their integration with technologies such as BIM, IoT and blockchain allows for more accurate forecasting, better risk mitigation and increased stakeholder accountability. As these systems evolve, they offer the potential for smarter, more sustainable and equitable construction practices. Future developments should focus on expanding interoperability, real-time decision-making and human-centered design.

3.4. BIM-GIS Integration Platforms for Underground Utility Infrastructure

This section explores the integration of BIM and Geographic Information System (GIS) in the lifecycle of Underground Utility Infrastructures (UIIs), which include water, sewage, gas, and electricity networks. Due to their complex and spatially distributed nature, UIIs benefit significantly from combining the detailed modeling capabilities of BIM with the extended spatial analysis capabilities of GIS [82]. In the water sector [83], as well as for gas pipelines [84] and power lines [85], the integrated use of BIM and GIS enables more accurate and efficient asset management, providing significant benefits throughout all stages of the infrastructure lifecycle. Additionally, BIM-GIS integration for UIIs through digital platforms allows processes to be simplified by enhancing usability and accessibility. The UII lifecycle can be broadly simplified into three main stages: planning, construction, and operation and maintenance (O&M). This paper categorizes existing digital platforms for BIM-GIS integration for UIIs according to the primary stage of the infrastructure lifecycle they address (Figure 5). Notably, there is no dedicated paragraph for the construction stage, as the literature lacks digital platforms that focus exclusively on this stage. At the end, a paragraph is included to report platforms that address multiple stages of the UII lifecycle with equal attention.

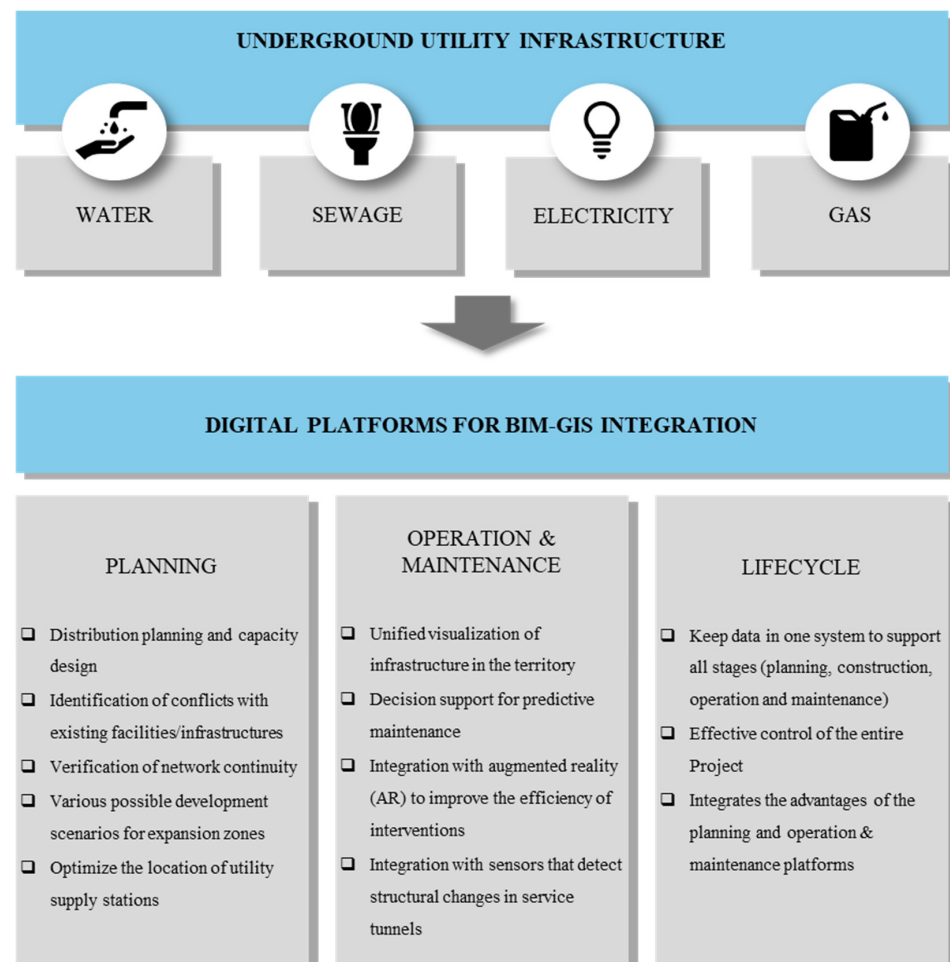


Figure 5. Benefits of digital platforms for BIM and GIS integration for underground utility infrastructures, according to the primary stage of the lifecycle they address.

3.4.1. Digital Platforms with Focus on Planning Stage

The literature shows that digital platforms are useful in supporting the planning stage. Being able to plan and design the distribution and capacity of UIIs accurately, before the

execution of works, offers benefits in terms of economics and timing. In particular, the importance of 3D modeling of UUIs in digital BIM-GIS integration platforms is emphasized to achieve this goal [86]. For example, the planning of water distribution systems, as with other UUIs, requires an integrated 3D BIM-GIS visualization model to set up topological validation rules, being able to identify and resolve conflicts between the project and existing infrastructure and verify network continuity [87]. The proprietary ArcGIS platform facilitates the integration of BIM pipeline design data, geospatial ground surface information and existing building models, enabling a comprehensive 3D representation in which topological validation rules are set. In addition, Wang et al. [88] point out that to make 3D visualization of pipelines effective, the development of specific visualization optimization algorithms is necessary. A fundamental benefit of digital platforms applied in this field is the possibility of creating various UUI network development scenarios for expanding cities [89]. By hypothesizing new buildings in the expansion area through BIM models, with their infrastructure needs (freshwater needs, sewer capacity, electricity needs, etc.), and integrating them into a GIS scenario, it is possible to plan the distribution and flow of UUIs. Finally, it is essential to optimize the location of utility supply stations, such as water tanks or electrical substations, based on the demand for services in each area. The tool proposed by Rabia et al. [90] for Autodesk Revit, named “BIM_UNOPT”, integrates BIM and GIS for optimizing the location of utility supply stations based on genetic algorithms, allowing designers to operate in a single platform without having to manually transfer data between platforms.

3.4.2. Digital Platforms with Focus on Operation and Maintenance Stage

While platforms in the planning stages focus on scheduling and designing future scenarios, platforms in the O&M stage focus on operational continuity and avoiding inconveniences. In this stage, it is essential to consolidate all building and infrastructure data within a unified digital environment, supported by comprehensive 3D visualization. Digital platforms are a valuable ally in achieving this goal. A notable example is the digital platform “BGIP” (BIM/GIS Integration Platform), which integrates information from hydraulic and hydropower engineering projects into a single environment, with the aim of improving information management and data visualization [91]. Underlying digital platforms are typically one or more databases, which are essential for storing and managing information. The information collected in the databases underlying the platforms plays a key role in ensuring the efficient maintenance of infrastructures. In particular, the maintenance of UUI tunnels is crucial to avoid inconveniences due to interruptions in drinking water, electricity and gas services. To address the challenges of infrastructure maintenance, Lee et al. [92] developed a digital platform that integrates a maintenance management system with 3D BIM-GIS visualization. This proposed solution supports utility tunnel O&M by overcoming the visualization limitations of previously proposed systems. Next, the digital platform proposed by Wang et al. [93] introduces additional functionalities by integrating BIM and GIS and a decision support system to improve the efficiency of maintenance works, both at the individual component level and at the network level. A particularly noteworthy example is the “Pipeline Operation and Maintenance Management System” (POMMS), which integrates BIM, GIS and Augmented Reality (AR), further improving the efficiency of maintenance operations, with a particular focus on gas pipelines [94]. An “Application Programming Interface” (API) has been developed within the proprietary Autodesk Navisworks platform, which serves as the interface for the maintenance system. The system also uses a digital AR platform, which allows the maintainer to connect and visualize the pipeline network during in situ works. The implementation of AR in digital platforms is a topic of growing interest; Rajadurai et al. [95]

also developed a framework for the integration of BIM, GIS and AR to improve the visualization and management of UIIs. This again involves the use of a digital platform that provides a realistic representation of UIIs directly in situ. Finally, the importance of sensor integration in O&M platforms should not be underestimated. In this view, the platform developed by Lee et al. [96] is proposed as a digital twin for UII management. The proposed platform integrates BIM, GIS and a multimodal image sensor, incorporating LiDAR technology, from which, through an algorithm, it is possible to detect structural changes in UII tunnels, enabling the prediction of possible failures [97].

3.4.3. Digital Platforms with Multi-Stage Lifecycle Focus

In addition to the digital platforms described above, which focus on the planning stage or O&M stage, there are some that are developed to support multiple stages of the lifecycle of UIIs. The most ambitious framework is the one proposed by Bansal [98], which leverages the proprietary ArcGIS platform, with support from Autodesk Navisworks and Autodesk Revit, to manage data across all stages of a building's lifecycle. The goal is to optimize the planning, design, construction, maintenance and demolition of buildings in relation to connected infrastructure, such as UIIs. The platform proposed by Ma et al. [99] is also based on ArcGIS, but with the more specific goal of supporting the relocation and modification of UIIs throughout their lifecycle by combining the potential of BIM and GIS. The platform merely exploits the potential of ArcGIS without proposing a real advance in research. More interesting, however, is the "3D City Integrated Pipe Network" platform proposed by Huang et al. [100], which supports first the planning stage, then the planning approval and analysis stage, and finally the construction completion verification stage. The developed digital platform integrates BIM and GIS data to support multiple stages of the life of UII construction projects [101]. Another important issue involving all the stages is the integration with road infrastructure, since UIIs in urban areas are usually located under roads. The integration model proposed by Rajadurai et al. [102] aims to assist the relocation of utilities in relation to road infrastructures by involving the planning stages of the intervention, facilitating coordination in relocation and ensuring effective management. The current model was primarily developed using the proprietary Autodesk Civil 3D platform, making further development necessary to achieve the stated goals. Finally, as highlighted in the literature, there is currently no BIM-GIS platform specifically dedicated to the construction stage of UIIs. The system proposed by Sharafat et al. [103] comes closest to this purpose, as it provides real-time visual support to operators as they work on UIIs, improving safety on the construction site. However, the BIM-GIS integration platform, again based on ArcGIS, supports not only the construction stage but also the planning and management stages of UIIs.

In conclusion, the integration of BIM and GIS through digital platforms offers promising advancements in the planning, operation and maintenance, and full lifecycle of underground utility infrastructures. While current platforms demonstrate considerable capabilities, future developments should focus on interoperability, open-source solutions, and integration with smart sensing and AI technologies to enhance scalability, flexibility and predictive capabilities across urban systems.

3.5. Digital Platforms in the Energy Sector

Emerging as transforming tools in the energy sector, digital platforms are promoting innovation and tackling the challenges of a rapidly evolving landscape [104,105]. In this context, they play a crucial role in contributing to the transition toward a more sustainable national energy system by accelerating the use of renewable energy sources (RESs) and optimizing energy efficiency [106]. By means of the integration of digital technologies and

growing interconnection, these platforms provide innovative solutions for optimizing energy market management, dynamically coordinating supply and demand, and so attaining better degrees of efficiency [107,108]. The evolution of digital platforms is transforming them from simple monitoring and control tools into comprehensive ecosystems for the intelligent management of energy assets [109]. Their capacity to integrate heterogeneous data from numerous sources and models is crucial for this transformation since it allows advanced simulations, in-depth investigations and more informed decision-making procedures [110,111]. Particularly in smart grid infrastructures, these platforms provide key functions for sophisticated simulation, effective consumption management and grid control, allowing one to manage and coordinate complicated energy systems [112–114]. Currently, the energy market includes a rising number of operational platforms, many of which are dedicated to RES. Their applications range from the management of energy communities to enhanced modeling allowed by cutting-edge technologies such as digital twins, with particular attention to the social effects related to their deployment, as shown in Figure 6.

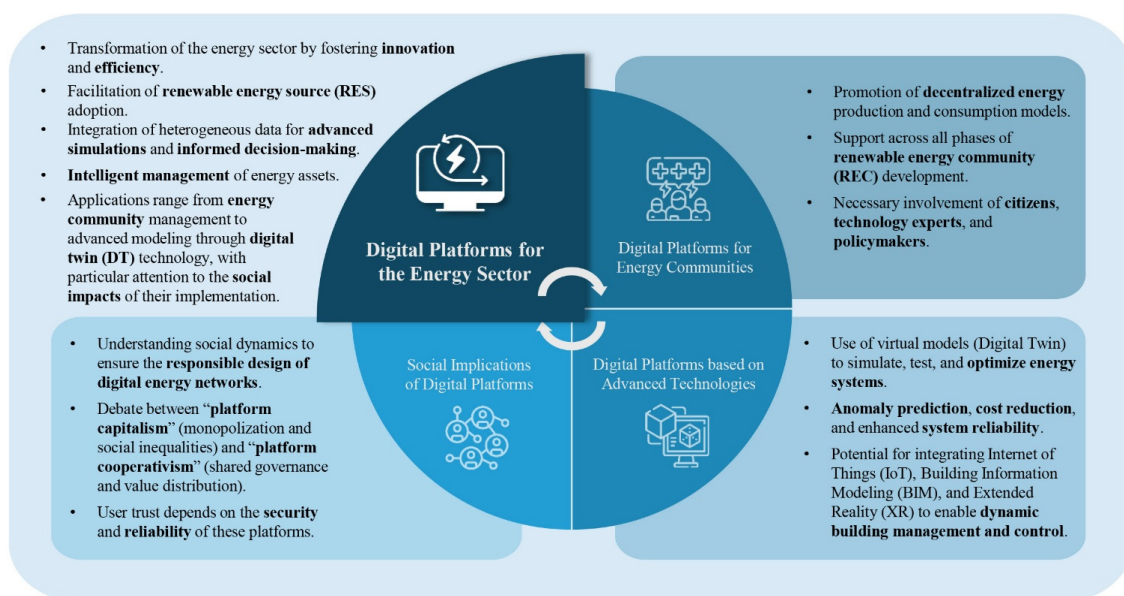


Figure 6. Overview of digital platforms for the energy sector: key points on energy communities, advanced technologies and social implications.

3.5.1. Digital Platforms for Energy Communities

A significant area within the ecosystem of digital platforms for energy is represented by those intended for energy communities. These digital tools play a crucial role in facilitating the transition to a more decentralized model of energy production and consumption, supporting the large-scale adoption of RECs. In response to the growing demand for technological support solutions, various digital platforms are emerging. Depending on the context that has driven their development, these platforms can be categorized as commercial solutions, freeware or open-source tools or platforms developed within European Union (EU)-funded projects [115]. Minuto et al. [115] reviewed 30 digital platforms and tools designed to cover each of the three phases of REC project implementation, supporting their management throughout the entire project lifecycle. The primary objective of the “design” phase is to initiate the REC project and develop a comprehensive feasibility study. The goal of the “creation” phase is to identify the means, procedures and resources necessary to establish the REC setup. Finally, the main objective of the “operation” phase is to ensure the effective management and maintenance of the REC. The findings highlight that the “design” and “operation” phases have a larger number of dedicated tools, while the

“creation” phase is solely explored in EU-funded projects. In this regard, Hill et al. [116] suggest using an online one-stop-shop (OSS) digital platform in energy community projects to support all stages of development in a single, integrated place. It is also important to note that the involvement of all key stakeholders (citizens, technology experts, and policymakers) is essential to ensure the effective implementation of energy projects. The purpose of the digital platform is to bridge the gap between the potential offered by energy communities and their actual implementation by groups of citizens without advanced technical expertise [115]. By providing integrated solutions for both administrative and technical management, these platforms help improve transparency, simplify decision-making processes and increase the effectiveness of investments in the sector.

3.5.2. Digital Platforms Based on Advanced Technologies

A rapidly increasing area of research concerns the use of digital twin-based platforms, owing to their capacity to adopt a modeling approach in the management of the lifecycle of energy systems. By creating a virtual model that correctly mimics the real energy system, the DT enables the simulation, refinement and validation of each design choice or operational decision prior to implementation [117]. The combination of these technologies proves particularly advantageous for the management of smart grids and industrial energy systems (IESs), where generation variability needs enhanced and dynamic system management [118,119]. Through the analysis of enormous volumes of data, these platforms enable anomaly prediction, operational cost reduction and increased reliability of energy systems. However, to ensure effective energy resource management, a DT-based platform must be well designed, incorporating data collection and pre-processing functions, storage, digital model construction, and analysis and visualization of results [120]. This structure is also particularly useful in the initial design phase through to the operational management of buildings [61]. The architecture of such platforms includes the creation of 3D virtual twins and dynamic updates via real-time data collected from IoT sensors, BIM models of the building and XR (Extended Reality) technologies, all within a unified environment [121]. The immediate processing of information allows these platforms to reflect the current state of the physical system, enabling the instant detection and resolution of potential instabilities [122]. Furthermore, the integration of this technology with AI systems opens significant advances in the energy industry, particularly in the predictive analysis and management of building energy consumption [59,121]. Current research in this field is focused on the integration of emerging technologies, such as AI, and the establishment of shared ontologies to improve semantics and interoperability between multiple digital models [123].

3.5.3. Social Implications of Digital Platforms

Digital platforms in the energy business raise substantial ethical and social challenges in addition to technological and operational ones [124]. By encouraging active user participation and bringing in new models of energy governance, the adoption of these platforms is changing the dynamics of energy production and consumption. Research conducted by Bartczak [125] has highlighted a generally positive attitude toward these platforms, both among representatives of companies that install RES systems and among end users. However, the adoption of digital platforms is reshaping the paradigm of energy provision and management, sparking a debate between two opposing economic models: “platform capitalism” and “platform cooperativism” [126]. While these models can be broadly applied across various sectors and carry wider socio-economic implications, the energy industry provides a particularly noteworthy example to highlight their fundamental principles, as well as their potential benefits or drawbacks. The former prioritizes the interests of

platform owners over those of users, which leads to monopolization and the escalation of social inequality. In contrast, the latter promotes a collaborative management model where users actively engage in the ownership and governance of platforms, hence promoting the generation of shared value. Overall, stakeholder involvement is essential to the success of digital platforms [127], allowing for local energy management optimization and promoting global collaboration in renewable energy and research [128,129]. Notwithstanding the many advantages, the application of these technologies also generates questions, especially about their possible influence on the privatization of energy provision, therefore impeding the shift to sustainable systems. For this reason, the participation of social sciences is not only necessary for examining ongoing developments but also for supporting the conscientious design of digital energy networks. Key elements in the acceptance of digital platforms in the sector include social readiness and the perception of benefits, although particular attention should be made to addressing security and dependability issues to build user confidence and assure the effectiveness of the system [130].

By allowing more distributed, efficient, user-centered energy systems, digital platforms are drastically changing the energy sector. Their interaction with newly developed technologies such as AI and digital twins promises even greater capabilities for participatory government, simulation and control. Nevertheless, future advancements must address concerns about data security, social equity and the risk of monopolization, ensuring that the digital transition remains both inclusive and sustainable.

3.6. Digital Platforms in Public Administration and Governance

Technological evolution has led the public sector toward a digital transition that aims to increase, in an increasingly assiduous way, the use of digital platforms within the public administration (PA). These platforms represent an opportunity to reshape and reorganize the intrinsic dynamics of the public sector, and their development and scope for improvement are still evolving [131]. In general, digital platforms bring many benefits to the PA as they facilitate the exchange, retrieval and management of data and information flows, allowing the administration to provide more transparency on the state of administrative practices and processes. They promote the active participation of those citizens most involved in planning decision-making processes and simplify and speed up the delivery of public services, reducing time and costs [132]. Thus, thanks to digital platforms, a PA more oriented toward the service of the community and the improvement of citizens' quality of life is evolving, thereby contributing to the creation of public value [133].

Under the topic of digital platforms for public administration, the literature review identified two sub-themes where digital platforms have been used. One of the most investigated topics concerns the world of participatory platforms, which are tools that enable the active participation of citizens in decision-making processes and encourage participatory oversight to improve public accountability and strengthen the bond between institutions and citizens. The second one is the theme of e-government platforms, whose main objective is to simplify and automate the interaction between citizens, institutions and public administration through the digitization of public services. Closely linked to the latter is the subject of open data, information database systems managed by the PA and made available in an open, accessible and reusable format to create an information network between institutions, businesses and citizens.

3.6.1. Participatory Platforms

The platforms can be seen as tools to facilitate communication and the relationship between the administration and citizens (Figure 7). Indeed, in this regard, Janowski et al. [134] investigate the relations between citizens and administration, identified based on scientific

literature, categorizing them into dominant governance paradigms and showing that they are ultimately all accumulated by the platform paradigm. A method for renewing the urban planning system and involving citizens in the decision-making process is sentiment analysis (SA), which is the process of collecting users' opinions on social platforms and similar. In fact, US scientists have developed an algorithm for analyzing the degree of satisfaction with products and services on the web. It is a trusted tool, as a user who is expressing opinions on the web is often influenced by the thoughts of others in the course of real life, unconsciously transforming him into a spokesman for a broader and more widespread opinion [135].

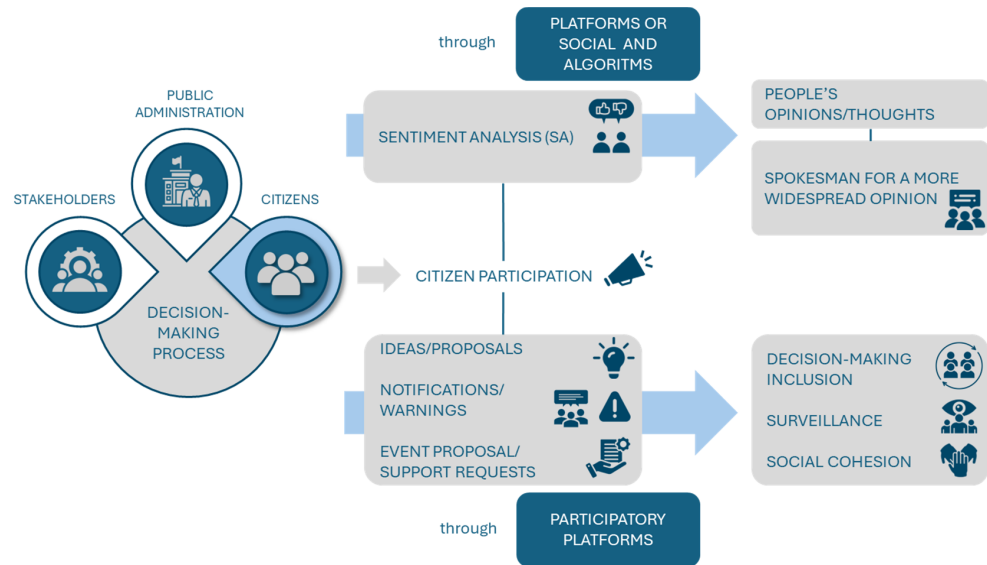


Figure 7. Schematic representation of the ways of including citizens in decision-making processes through platforms.

The participatory platforms can integrate different functions, such as enabling citizens to actively participate in defining the identity and future direction of their neighborhoods, offering a space for groups and individuals to share ideas, organizing events and mobilizing resources to improve their community and facilitate exchange and engagement between individual citizens on neighborhoods issues by promoting community cohesion and mutual help. In addition, to achieve effective citizen involvement, it is necessary to build trust by ensuring transparency in the process, using appropriate language and offering an intuitive interface [136]. These co-production platforms are applied globally, both in small-scale contexts and oriented to the redesign of a specific object or service, a forward-looking planning process aimed at producing an overall planning vision for the city [137]. In Spain, Madrid has implemented an open software platform named Consul, which is an online portal with different areas of participation divided into three main phases: presentation, support and voting. So, anyone can create a proposal, and those most supported by the citizens can finally be voted on; if the votes in favor are greater than those against, the proposal is accepted as a “collective proposal” of the citizens that the government approves and implements [138]. In India, in the city of Bhubaneswar, the platforms adopted promote and encourage hierarchical and participatory surveillance. The Bhubaneswar Land Use Intelligence System (BLUIS) platform works through a mobile app and, through citizen reports, monitors the invasion of public lands using satellite data. Instead, the Building Plan Approval System (BPAS) automates the approval of building plans, and the Digital Door Numbering System (DDNS) streamlines municipal service delivery and oversight by assigning a specific digital code to all households [139].

3.6.2. E-Government Platforms and Open Data

Moving from participatory platforms to e-government systems, the following section explores e-government platforms that are more standardized in France, Italy, and the United Kingdom than participatory platforms and open data because they are based on established, technical, organizational and political knowledge. On the contrary, open data, as well as participatory platforms, are still undergoing an experimental phase characterized by fragmentation and uncertainty [140]. Open data (OD), which in Italy is regulated by art. 9 of the Decreto Crescita 2.0 (Law 221/2012), is considered a true information infrastructure serving citizens and democracy, capable of enabling information flows, and participatory communication may greatly benefit political and administrative decision-making and the work of public administration in general [141]. Instead, still in Italy, e-government platforms are also called “enablers”, as they allow citizens and PA entities to perform certain actions digitally. There are several, depending on the service they can offer, such as the SPID platform which verifies digital identity at national level, allowing citizens to access all public administration online services in a secure way, or PagoPA, a platform enabling citizens to pay taxes, service fees and public charges online in a safe and easy way [142]. In Brazil, the progress in digital transition achieved by the Brazilian PA is evident from the use of various digital government platforms, as Brasil Cidadão, a platform that offers a single authentication service for citizens to access government services, Conecta-Gov, for information sharing between government agencies, GovData, which simplifies access to databases, and many others that help improve the delivery of public services and bring citizens closer to the administration [143]. Nevertheless, a performance evaluation study of the Brazilian eGov platforms states that few of them are top-performing and come from more developed regions in Brazil [144].

Digital platforms are not only technological enablers but also powerful instruments of institutional reform. Their integration within public governance—through participatory mechanisms, digital public services and open-data ecosystems—marks a shift toward greater transparency, responsiveness and accountability. Yet, to realize their full potential, ongoing challenges in standardization, digital inclusion and interoperability must be addressed. A future-proof digital administration will depend on a human-centered, inclusive and adaptive approach to platform governance.

4. Discussion (Cross-Domain Synthesis)

As shown in Table 3, digital platforms across the domains under review undertake multiple roles that range from predictive analytics and decision support to participatory governance and lifecycle cost management. Although these platforms have specific needs of the particular industries they address, comparative analysis across domains brings out the convergence of the opportunities and enduring structural constraints that adversely limit their maturity and scalability, as well as their transformative potential.

To provide a more concrete evaluation of technological maturity, the framework of Technology Readiness Levels (TRLs) is introduced. This helps assess the developmental stage and implementation feasibility of emerging technologies. Mature technologies such as BIM, IoT systems and traditional dashboard interfaces operate at TRLs 8–9, indicating full deployment in commercial and operational contexts. In contrast, innovations like large language models (LLMs), federated learning and immersive environments (AR, VR, XR) remain at TRLs 3–5, as they have been validated within niche applications related to the built environment. Similarly, the Metaverse, discussed as a virtual model of platform urbanism, remains conceptual (TRLs 2–4), hindered by technological, legal and organizational readiness gaps.

Table 3. Cross-domain synthesis of digital platforms in the built environment.

Domain	ID	Primary Functions of Platforms	Typical Enabling Technologies	Main Limitations	Emerging Trends
Artificial Intelligence	AI	Predictive analytics, automation, risk mitigation, design optimization	ML, DL, Computer Vision	Lack of interoperability, high computational cost, legal and ethical concerns	AI-assisted planning, generative design, platform personalization
Digital Twins	DT	Real-time monitoring, simulation, infrastructure and urban system management	IoT, BIM, AI, 3D Modeling, Cloud Services, Microservices	Semantic interoperability, real-time data integration, system complexity	Urban Digital Twins, predictive maintenance, citizen engagement
Lifecycle Cost Management	LCM	Cost forecasting, transparency, lifecycle traceability, maintenance scheduling	BIM, IoT, Blockchain, Real-Time Dashboards	Fragmented data sources, lack of domain integration, low adoption	Blockchain-enabled traceability, integration with scheduling tools
BIM-GIS for UUIs	BGU	3D visualization, utility planning, tunnel and pipeline maintenance, on-site data access	BIM, GIS, AR, LiDAR, Decision Support Systems	Lack of platforms for construction phase, proprietary tools, limited standardization	Integration with smart city platforms, use of AR for O&M
Energy Sector	ES	Energy monitoring, grid optimization, energy community governance, on-site data access	Digital Twins, AI, IoT, BIM, XR	Data privacy, governance model conflicts, user digital readiness	Platform cooperativism, predictive energy balancing, DT-driven building management
Public Administration	PA	Participatory planning, e-government services, open data access	Web Platforms, Sentiment Analysis, Open Data Systems	Institutional inertia, digital divide, low platform interoperability	AI-supported participatory tools, standardization of open data protocols

In all the sectors considered, digital platforms have shown high added value in enhancing decision-making based on information, accelerating the integrated management of complex systems, and assisting in real-time monitoring of assets, processes and financial flows. The fusion of technologies such as BIM, IoT, AI, digital twins, GIS and blockchain has transformed platforms from their original positioning as repositories of information toward multifaceted orchestrators of dynamic environments with information that enable predictive, participatory and sustainability-focused services.

Nonetheless, the comparative cross-sectoral synthesis brings into focus that these advantages are systematically confronted by a range of recurring constraints that cut across sectoral boundaries and capture the systemic socio-technical, organizational and institutional impediments. In spite of the variety of the contexts under examination—which range from cost control, public services, energy networks, underground infrastructure, AI technologies and digital twins—the impediments that one faces are convergent in nature and in their consequence for sectoral and organizational transformation. These observations further underscore the awareness that the digital transformation in the built environment is not merely hindered by technical impediments that are specific to the sectors but by more general systemic factors that prefigure both technological and organizational challenges [145–147].

Additionally, a major integration challenge involves data interoperability and semantic coherence across spatial scales (building, neighborhood, urban, regional) and lifecycle stages (design, construction, operation, end-of-life). Digital platforms often operate with scale-specific data granularity, e.g., BIM models at the object/component level versus GIS datasets at the territorial level, which complicates integration. Therefore, the implementation of hierarchical ontologies that define entity relationships across spatial and functional levels is critical. For example, nested relationships (e.g., “door” within “room” within “building” within “urban block”) must be modeled using aligned metadata schemas and linked data techniques. These ontologies should also support bidirectional data flows, allowing both top-down (e.g., policy-to-asset) and bottom-up (e.g., sensor-to-system) integration.

To critically read these constraints, they have been organized into the four macro-categories of data, usability, processes and sustainability as presented in Table 4. This categorization brings forth the prevalence and long-term nature of these challenges and offers a basis for postulating directions for cross-sectoral and cross-scalar R&D.

Table 4. Systematization of the limitations of digital platforms found in the cross-domain review.

Macro Categories	Recurrent Limitations	Code n.	DT	PA	LCM	AI	ES	BGU			
Data	Lack of interoperability with legacy data	L01	Legacy data often fragmented across formats, including outdated digital files and, in some contexts, paper-based archives; incompatible file types and lack of standardization	Legacy data often fragmented across formats, including outdated digital files and, in some contexts, paper-based archives; incompatible file types and lack of standardization	Legacy data often fragmented across formats, including outdated digital files and, in some contexts, paper-based archives; incompatible file types and lack of standardization	Legacy data often fragmented across formats, including outdated digital files and, in some contexts, paper-based archives; incompatible file types and lack of standardization	Legacy data are usually paper-based or stored in proprietary file formats	Legacy data often fragmented across formats, including outdated digital files and, in some contexts, paper-based archives; incompatible file types and lack of standardization			
			data inconsistency and ambiguity	L02	Unchecked data duplication across multiple databases	Unchecked data duplication across multiple databases		Unchecked data duplication across multiple databases	-	-	Unchecked data duplication across multiple databases
					lack of accessible and standardized data formats	L03		Unstructured data	Unstructured data	-	-
	Usability	large-scale data integration	L04	Lack of data integration methods across different scales and domains	-	Lack of data integration methods across different scales and domains	Lack of data integration methods across different scales and domains (only for purely data-driven models)	-	Lack of data integration methods across different scales and domains (e.g., large-scale sensing and models)		
				Privacy and data security issues	L05	Personal data vulnerability, sensitive information theft, potential damage to IT systems	Personal data vulnerability, sensitive information theft, potential damage to IT systems	Personal data vulnerability, sensitive information theft, potential damage to IT systems	Personal data vulnerability, sensitive information theft, potential damage to IT systems	Personal data vulnerability, sensitive information theft, potential damage to IT systems	Personal data vulnerability, sensitive information theft, potential damage to IT systems
		Expert skills required (limiting usability on large scales)	L06			Innovative technologies in traditional analog processes	Shortage of trained personnel ready to use digital platforms	-	Shortage of AI-skilled professionals	-	-
				Lack of user involvement with the platforms	L07	Lack of interactive and user-friendly interfaces	Lack of interactive and user-friendly interfaces	-	-	-	Lack of interactive and user-friendly interfaces

Table 4. Cont.

Macro Categories	Recurrent Limitations	Code n.	DT	PA	LCM	AI	ES	BGU
Processes	Risk of parallelized human-machine decision-making	L08	Implicit AI models for decision-making activities	PA personnel cannot understand implicit algorithmic decisions (for implicit AI models only)	-	Data-driven only models are not explicit	-	-
	Difficulties in addressing uncertainty in complex scenarios	L09	Partial and variable input data	Partial and variable input data	Partial and variable input data	Partial and variable input data	Partial and variable input data	Partial and variable input data
	Implementation costs	L10	Cross-domain feature implies more efforts in terms of required investments	Processes based on conservative business models.	Cross-domain feature implies more efforts in terms of required investments	-	-	-
Sustainability	Social implications	L11	-	-	-	Public concerns about biased machine decision-making	Public concerns about unequal access to energy resources	-

The first macro-category of limitations observed in the review concerns data quality, availability and interoperability. Throughout the above sections, emphasis is placed upon the fact that digital platforms cannot offer the maximum of their capabilities without taking advantage of accessible, consistent and thus standardized and integrated data while also taking into consideration multiple scales (levels of detail) and domains of operation [148]. Integrating data across scales further requires designing ontological frameworks capable of bridging granular object-level BIM datasets with abstract GIS and statistical models, often deployed at urban or regional scales. This involves the explicit mapping of semantic terms and units (e.g., energy use per square meter in BIM to district-level consumption in GIS), as well as ensuring consistency in spatial reference systems and temporal resolution.

Data that are thus both structured and disambiguated between different scales and domains and consequently mutually linked [149,150], even in real time [151–153], including the essential connection with legacy data already available but typically found in non-standardized formats. However, this drive toward integration must be balanced with privacy and cybersecurity concerns, especially when integrating sensitive user data or operational parameters across platforms. Ensuring that data sharing does not compromise confidentiality while enabling transparency and reuse is a critical technical and ethical challenge. In this regard, an example of critical legacy data is that related to infrastructure assets, usually collected and structured within Asset Management Systems (AMSs) [154]. It all goes back to the problem of information fragmentation [155], mainly driven by conventional siloed approaches rather than a systemic view [156–158].

The second cluster of recurrent limitations concerns factors related to the usability of platforms. They include the user's capacity to use the available digital tools in today's processes, the user's involvement in the procedures of digital platforms, and the alignment between the functionality offered by the platform and the context requirements. These kinds of limitations arise very frequently from the intention to embed innovative technologies

in processes and business models that are not equally developed, which may also be totally reliant on paper-based documentation. In fact, the construction sector, particularly the public administration and energy and utilities infrastructure-related sub-sectors, is characterized by analog processes and conservative business models and, therefore, is reluctant to the introduction of digital technologies [145]. Institutional inertia and the complexity of existing regulations [146] in the areas analyzed hinder the introduction of innovative methodologies based on DT and AI [16,159] that could reduce the need for expert knowledge, mainly concentrating it at the decision-making levels, where it is truly indispensable [160,161].

The third set of identified limitations concerns process fragmentation. This is closely related to the previous two sets of limitations. Indeed, traditional processes and their fragmentation affect the quality of data and the introduction of usable digital systems, and vice versa [145]. Also, in scenarios where data are available, the absence of proper digital processes undermines their successful use. These issues are evident in the complex scenarios analyzed in this paper: energy infrastructure, underground utilities and public works in the first place. This is also reflected, therefore, on the issue of cost management. Indeed, its cross-cutting nature suffers from the fragmentation of processes and results in the lack of true platforms centered on this theme. Yet, few studies address process modeling and automation in the construction sector with the introduction of digital technologies and according to a process-centric approach [146]. Digital twinning and AI solutions do not yet appear to be particularly mature for digital process transformation, first, because of the strict need to largely rely on experienced personnel to monitor compliance with technical, administrative and regulatory dictates [162], and second, because of the inability to understand non-explicit algorithmic decisions [160], especially where the most modern machine learning and deep learning models are used and where uncertainty variables are present. The self-evident dangerous consequence for public administrations and infrastructure managers is the human/machine parallelization of decision-making activities [163].

Within the last set of limitations analyzed are those related to economic and social sustainability. These constraints, particularly implementation costs, have been estimated in recent studies. For instance, EU-funded research on energy platforms indicates that initial deployment costs for interoperable smart systems in public buildings can range between EUR 100,000 and EUR 500,000, depending on scale, while operational savings of up to 20% on annual energy bills have been documented [164]. Similarly, lifecycle cost evaluations of BIM-integrated asset management platforms show potential return on investment (ROI) within 3–5 years when applied at city-scale infrastructure networks [165].

Furthermore, incorporating TRL perspectives clarifies the maturity gaps between technologies. Digital twins and BIM-GIS platforms, for example, are at TRL 6–8, yet their broader deployment is hindered by issues of semantic interoperability, legacy data integration and platform silos. In contrast, technologies such as federated learning, which offer privacy-preserving and distributed AI training, remain at proof-of-concept stages in the built environment and face challenges related to data governance, computational infrastructure and legal compliance. These differences in maturity demand tailored R&D strategies that account for both readiness and application domain.

The Metaverse provides another instructive case. While promising for virtual participatory governance and immersive urban simulation, its current applications are limited. Pilot projects in cities like Seoul and Singapore are still in exploratory phases, with widespread implementation constrained by interoperability issues, accessibility of hardware, digital literacy and policy uncertainty. As such, the Metaverse in its current form is best positioned at an experimental TRL, reinforcing the need for incremental adoption supported by cross-sectoral testbeds and collaborative development frameworks.

The analysis of the recurrence frequencies of the identified limitation categories (Figure 8) provides further evidence of their structural nature, rooted in each of the areas investigated in this paper.

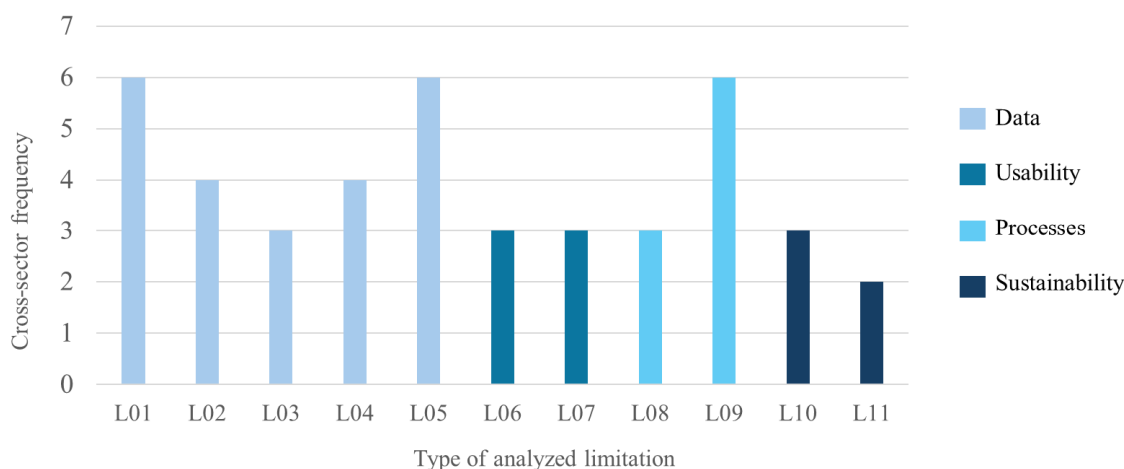


Figure 8. Recurrence analysis of current limitations of digital platforms in the examined domains.

Overcoming the constraints shared in most of the cases analyzed, as highlighted above, requires a systemic approach [161,166]. Responding to the most frequently encountered limitations, specific directions for research and development are proposed below.

With regard to the category of limitations for the development of digital platforms concerning data, standardized multi-domain and multi-scale ontology frameworks development and adoption are a viable solution [149]. Despite the semantic web and the latest linked data technologies, standardization requires the major effort of categorizing entities and processes, particularly challenging in complex systems featuring completely unexpected dynamics [167]. Nevertheless, the integration of different ontologies into complex descriptive frameworks can leverage the large number of ontologies and data dictionaries already developed. This means that only the linking models between them should be developed. The example of the EUROTTL framework is given, which was developed in this perspective as an aggregation of existing heterogeneous dictionaries for modeling complex road infrastructure systems, maintenance processes included [168]. To be successful, these modeling approaches must be coupled with the development of modular platforms, mainly based on a microservices-based system architecture [157,169,170]. This ensures scalability and ease of multi-domain and multi-scale data integration, while simultaneously enabling automated data analysis procedures. Legacy data integration functions can also be incorporated into these systems following approaches of data conversion [171] and data structuring [172]. Simultaneously, the structuring of heterogeneous data according to semantic web-based methodologies enables the creation of accessible and queryable platforms [157,170], along with the implementation of simplified data access and control procedures, also using immersive visualization tools such as automated AR technologies [173,174]. Furthermore, privacy and data security issues can be addressed by integrating distributed ledger technologies [175]. These offer tamper-proof audit trails and decentralized access control, which can help mitigate risks of unauthorized data manipulation or breaches. Nevertheless, they introduce trade-offs in terms of scalability, latency and compliance with data protection regulations such as GDPR. Therefore, careful architectural design is required to optimize between openness, control and legal conformity.

Regarding the limitations inherent in usability and processes, there is a need to reduce intermediate human control procedures (e.g., code checking, classification and categorization, etc.) by outsourcing them to appropriate AI models [172]. This would reduce

the expertise needed at the low level, delegating it to the high-level decision-making and control phase only [161]. Reducing manual activities through process automation is thus key to unlocking the potential of digital platforms. Thus, process reengineering is urgently needed, although this can have significant initial costs. Critical to reengineering is reconsidering the role of digital platforms not just as an isolated tool but rather as an orchestrating ecosystem. Again, microservice-based and service-oriented platforms offer great potential [157,169,170]. This would also help the development of platforms whose focus is centered on cost management and has not yet been investigated in research. Pilot implementations of lifecycle cost management platforms in hospital infrastructure projects in Italy and the Netherlands have shown improved budget forecasting accuracy by over 25% compared with conventional methods, reducing overall project overruns [176]. However, adoption in smaller municipalities remains limited due to upfront capital and staff training costs, showing that economic feasibility is context-dependent. Concurrently, approaches based on expert systems [160,162] are found to be more suitable for solving decision-making parallelization given their inference capabilities in situations of uncertainty, underlying complex scenarios, than data-driven only AI models. For example, probabilistic approaches such as those based on Bayesian networks [177] avoid the risk of decision parallelization by first ensuring explicit inference models that are, therefore, governable at the decision-making level by experts. Secondly, they allow the integration of heterogeneous data and processes (including analytical ones) following concatenated probabilistic functions. Furthermore, they run even with partial input data, meeting the most common needs in situations of uncertainty.

Cross-domain insights from this paper suggest the need to develop service-oriented digital platforms as ecosystem orchestrators rather than isolated software. This orchestrator function is relevant in cross-scalar scenarios, where platforms must manage data at different levels of abstraction and spatial granularity. For instance, integrating IoT sensor data from individual building systems into regional digital twin environments requires real-time data normalization and alignment through middleware components that operate under a unified ontology layer. Such middleware must also include privacy-preserving computation protocols or federated learning models when sensitive data is involved, enabling analytics without centralized data exposure. Modular architectures foster customization and accessibility and enable third-party service integration. The development of platform-centric processes also supports the management of dynamic systems and guarantees a sustainable digital transformation. This perspective can guide future research efforts on digital platforms for the construction and built environment domain.

5. Conclusions

This paper presents an inter-sectoral review of digital platforms within the built environment on six thematic areas, namely, AI in construction, digital twins, lifecycle cost management, BIM-GIS for underground utilities, energy sector platforms and public administration. This study found that digital platforms are becoming essential enablers of digital transformation, having developed from mere technical tools into large-scale, complex socio-technical systems that are capable of coordinating data, technologies, stakeholders and governance across sectors, lifecycle phases and scales.

Digital platforms can now accommodate new services that include real-time decision-making, predictive maintenance, lifecycle optimization, participatory governance and sustainability-based strategies, and they integrate technologies like BIM, GIS, IoT, AI, digital twins and blockchain.

Despite this, the research indicates that widespread, systemic challenges still restrict their potential in all the domains that were analyzed. These include the following:

- Issues related to data, including fragmentation, inconsistency, lack of interoperability and privacy/security risks;
- Usability barriers, caused by limited digital skills and a lack of user engagement;
- Process fragmentation, causing inefficiencies and decision-making bottlenecks;
- Sustainability and governance issues, in terms of high deployment cost, socio-economic disparity and inadequate platform governance models.

These challenges are not just technological but deeply embedded in organizational, procedural, and governance frameworks, making them structural and systemic issues rather than sector-specific or technical limitations. To overcome these challenges, the article proposes a number of research and development strategies:

- Use of modular, microservice and service-oriented architectures for scalable, interoperable and flexible platforms;
- Development of multi-scale, multi-domain and standardized ontologies in order to harmonize and make data accessible and reusable;
- Merging explainable and probabilistic AI models that guarantee transparent, trustworthy and human-in-the-loop decision-making, particularly in uncertain and complex contexts;
- Redesigning workflows and processes into participative, process-based and data-centered digital environments;
- Establishment of transparent, participatory, and cooperative platform governance models aimed at fostering user empowerment and inclusiveness.

The article also draws attention to the promising yet underexplored potential of new technologies, including large language models (LLMs), immersive virtual spaces (AR, VR, XR) and federated learning architectures, that can improve handling of data, user experience and privacy-preserving data exchange. However, all of these technologies still have significant gaps in terms of their maturity, scalability, and interoperability, and, therefore, need research on ethics, governance, user acceptance and capacity building.

A gap in the literature is the Global South, wherein the majority of research does not consider the unique socio-economic, institutional and infrastructural contexts. While this paper focused on literature from the Global North, many of the structural challenges identified, such as platform fragmentation, low interoperability and governance barriers, are systemic and occur in underrepresented contexts as well. Emphasis is placed in this paper on the need for developing context-sensitive, frugal and inclusive platform models, co-designed with the local stakeholders, ensuring that digital transformation processes promote equity, inclusion, and resilience, and do not increase digital divides. Future research should address this gap by integrating literature and empirical evidence from underrepresented regions and by validating proposed models through case studies that reflect diverse geographical, cultural and institutional settings.

In terms of academic knowledge, this study contributes a novel cross-sectoral and cross-scalar synthesis of digital platforms in the built environment, introducing a multi-dimensional analytical framework that integrates technical, organizational, and governance perspectives. It expands the conceptualization of platforms beyond technological tools, framing them as socio-technical ecosystems capable of orchestrating data, processes, and stakeholder interactions across domains and lifecycle phases. This provides a foundation for the future theoretical development, empirical research and comparative evaluation of platform maturity and integration.

In terms of practical contribution, the findings serve as a reference for public administrations, platform developers, infrastructure managers and policy-makers by identifying shared structural barriers (e.g., fragmented data, limited interoperability, siloed processes) and outlining targeted strategies for overcoming them. These include scalable architectures,

inclusive governance models, and interoperable data frameworks, which can guide the design, implementation, and regulation of next-generation digital platforms. Furthermore, the review offers actionable insights to support the deployment of digital platforms that are human-centered, lifecycle-aware, and context-adaptable, particularly in urban development, infrastructure maintenance and energy management.

In conclusion, the article validates that digital platforms have the potential for transformation toward creating a more sustainable, efficient, resilient, and participatory built environment, but for this, there is a need for systemic, interdisciplinary, and user-centric approaches, harmonizing technological innovation with organizational, governance and societal-political transformations. Future research should be informed by empirical analysis, pilot projects and inter-sectoral collaborations with a clear priority for lifecycle cost management platforms, ensuring that platforms are made inclusive, flexible and adaptable for all contexts worldwide.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/buildings15142432/s1>, Figure S1: PRISMA 2020 flow diagram; Table S1: PRISMA 2020 checklist.

Author Contributions: S.C. and C.M. conceived and supervised the research, coordinated the structure of the paper, and carried out the overall revision of the manuscript. M.B., L.B., D.D., C.G., L.G., A.M. and B.M.T. each contributed equally by conducting the literature review and drafting the section of the paper corresponding to their assigned thematic domain. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: No datasets or code were generated or analyzed during the current study. All information used in this review is derived from peer-reviewed publications, which are cited throughout the manuscript.

Acknowledgments: This research was carried out within the framework of the ISTeA Giovani initiative, promoted by the Italian Society of Science, Technology and Engineering of Architecture (ISTeA), and coordinated by S. Cascone, F. Pittau, and M. Rotilio. The initiative aims to foster collaborative research and knowledge exchange among early-career researchers working on topics related to innovation, sustainability, and digital transition of the built environment. The activities were supported by the Department of Civil, Construction-Architectural and Environmental Engineering (DICEAA), Dipartimento di Eccellenza MUR 2023–2027, University of L'Aquila. L.B. has received funding from Task n. 4 “Education and Research” of the National Recovery and Resilience Plan (NRRP) and in particular component 2—investment 1.4, “Strengthening research facilities and creating ‘national R&D champions’ on some Key Enabling Technologies” funded by the European Union—NextGenerationEU—research program named “Sustainable Mobility Center (Centro Nazionale per la Mobilità Sostenibile—CNMS)” —application code CN_000023—CUP I33C22001240001.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Rafsanjani, H.N.; Nabizadeh, A.H. Towards Digital Architecture, Engineering, and Construction (AEC) Industry through Virtual Design and Construction (VDC) and Digital Twin. *Energy Built Environ.* **2023**, *4*, 169–178. [[CrossRef](#)]
2. Panteli, C.; Kylili, A.; Fokaides, P.A. Building Information Modelling Applications in Smart Buildings: From Design to Commissioning and beyond A Critical Review. *J. Clean. Prod.* **2020**, *265*, 121766. [[CrossRef](#)]
3. Osorio-Gómez, C.C.; Herrera, R.F.; Prieto-Osorio, J.M.; Pellicer, E. Conceptual Model for Implementation of Digital Transformation and Organizational Structure in the Construction Sector. *Ain Shams Eng. J.* **2024**, *15*, 102749. [[CrossRef](#)]
4. Brozovsky, J.; Labonnote, N.; Vigren, O. Digital technologies in architecture, engineering, and construction. *J. Autom. Constr.* **2024**, *158*, 105212. [[CrossRef](#)]

5. Horry, R.; Booth, C.A.; Mahamadu, A.; Manu, P.; Georgakis, P. Environmental Management Systems in the Architectural, Engineering and Construction Sectors: A Roadmap to Aid the Delivery of the Sustainable Development Goals. *Environ. Dev. Sustain.* **2022**, *24*, 10585–10615. [[CrossRef](#)]
6. Zhang, Z.; Wei, Z.; Court, S.; Yang, L.; Wang, S.; Thirunavukarasu, A.; Zhao, Y. A Review of Digital Twin Technologies for Enhanced Sustainability in the Construction Industry. *Buildings* **2024**, *14*, 1113. [[CrossRef](#)]
7. Asif, M.; Naeem, G.; Khalid, M. Digitalization for Sustainable Buildings: Technologies, Applications, Potential, and Challenges. *J. Clean. Prod.* **2024**, *450*, 141814. [[CrossRef](#)]
8. Teclaw, W.; O'Donnel, J.; Kukkonen, V.; Pauwels, P.; Labonnote, N.; Hjelseth, E. Federating Cross-Domain BIM-Based Knowledge Graph. *Adv. Eng. Inform.* **2024**, *62*, 102770. [[CrossRef](#)]
9. Lee, D.; Lee, S.H.; Masoud, N.; Krishnan, M.S.; Li, V.C. Integrated Digital Twin and Blockchain Framework to Support Accountable Information Sharing in Construction Projects. *Autom. Constr.* **2021**, *127*, 103688. [[CrossRef](#)]
10. Salzano, A.; Cascone, S.; Zitiello, E.P.; Nicoletta, M. HVAC System Performance in Educational Facilities: A Case Study on the Integration of Digital Twin Technology and IoT Sensors for Predictive Maintenance. *J. Archit. Eng.* **2025**, *31*, 04025004. [[CrossRef](#)]
11. Brandin, R.; Abrishami, S. Information Traceability Platforms for Asset Data Lifecycle: Blockchain-Based Technologies. *Smart Sustain. Built Environ.* **2021**, *10*, 364–386. [[CrossRef](#)]
12. Chen, X.; Chang-Richards, A.Y.; Ling, F.Y.Y.; Yiu, T.W.; Pelosi, A.; Yang, N. Digital Technology-Enabled AEC Project Management: Practical Use Cases, Deployment Patterns and Emerging Trends. *Eng. Constr. Archit. Manag.* **2024**, *32*, 4125–4154. [[CrossRef](#)]
13. Bosch-Sijtsema, P.; Claesson-Jonsson, C.; Johansson, M.; Roupe, M. The Hype Factor of Digital Technologies in AEC. *Constr. Innov.* **2021**, *21*, 899–916. [[CrossRef](#)]
14. Turk, Ž. Structured Analysis of ICT Adoption in the European Construction Industry. *Int. J. Constr. Manag.* **2023**, *23*, 756–762. [[CrossRef](#)]
15. Naji, K.K.; Gunduz, M.; Alhenzab, F.; Al-Hababi, H.; Al-Qahtani, A. Assessing the Digital Transformation Readiness of the Construction Industry Utilizing the Delphi Method. *Buildings* **2024**, *14*, 601. [[CrossRef](#)]
16. Serrano, W. Digital Systems in Smart City and Infrastructure: Digital as a Service. *Smart Cities* **2018**, *1*, 134–154. [[CrossRef](#)]
17. Ang, K.L.-M.; Seng, J.K.P. Application Specific Internet of Things (ASIoTs): Taxonomy, Applications, Use Case and Future Directions. *IEEE Access* **2019**, *7*, 56577–56590. [[CrossRef](#)]
18. Rabbi, A.B.K.; Jeelani, I. AI Integration in Construction Safety: Current State, Challenges, and Future Opportunities in Text, Vision, and Audio Based Applications. *Autom. Constr.* **2024**, *164*, 105443. [[CrossRef](#)]
19. Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. The PRISMA 2020 Statement: An Updated Guideline for Reporting Systematic Reviews. *BMJ* **2021**, *372*, n71. [[CrossRef](#)]
20. Jiang, X.; Jiang, X.; Sun, W.; Fan, W. How Do Manufacturing Firms Manage Artificial Intelligence to Drive Iterative Product Innovation? *IEEE Trans. Eng. Manag.* **2024**, *71*, 6090–6102. [[CrossRef](#)]
21. Bibri, S.E. The Metaverse as a Virtual Model of Platform Urbanism: Its Converging AIoT, XReality, Neurotech, and Nanobiotech and Their Applications, Challenges, and Risks. *Smart Cities* **2023**, *6*, 1345–1384. [[CrossRef](#)]
22. Çetin, S.; De Wolf, C.; Bocken, N. Circular Digital Built Environment: An Emerging Framework. *Sustainability* **2021**, *13*, 6348. [[CrossRef](#)]
23. Talla, A.; McIlwaine, S. Industry 4.0 and the Circular Economy: Using Design-Stage Digital Technology to Reduce Construction Waste. *Smart Sustain. Built Environ.* **2024**, *13*, 179–198. [[CrossRef](#)]
24. Scime, L.; Singh, A.; Paquit, V. A Scalable Digital Platform for the Use of Digital Twins in Additive Manufacturing. *Manuf. Lett.* **2022**, *31*, 28–32. [[CrossRef](#)]
25. Fang, W.; Ding, L.; Love, P.E.D.; Luo, H.; Li, H.; Peña-Mora, F.; Zhong, B.; Zhou, C. Computer Vision Applications in Construction Safety Assurance. *Autom. Constr.* **2020**, *110*, 103013. [[CrossRef](#)]
26. Homaei, M.; Mogollón-Gutiérrez, Ó.; Sancho, J.C.; Ávila, M.; Caro, A. A Review of Digital Twins and Their Application in Cybersecurity Based on Artificial Intelligence. *Artif. Intell. Rev.* **2024**, *57*, 201. [[CrossRef](#)]
27. Ieva, S.; Bilenchi, I.; Gramegna, F.; Pinto, A.; Scioscia, F.; Ruta, M.; Loseto, G. Enhancing Last-Mile Logistics: AI-Driven Fleet Optimization, Mixed Reality, and Large Language Model Assistants for Warehouse Operations. *Sensors* **2025**, *25*, 2696. [[CrossRef](#)]
28. Korkas, C.; Dimara, A.; Michailidis, I.; Krinidis, S.; Marin-Perez, R.; García, A.I.M.; Skarmeta, A.; Kitsikoudis, K.; Kosmatopoulos, E.; Anagnostopoulos, C.N.; et al. Integration and Verification of PLUG-N-HARVEST ICT Platform for Intelligent Management of Buildings. *Energies* **2022**, *15*, 2610. [[CrossRef](#)]
29. Chashyn, D.; Khurudzhi, Y.; Daukšys, M. Directions for the Formation of «City Intelligent Models» Using Artificial Intelligence for the Post-War Reconstruction of Historical Buildings. *Bud. Archit.* **2024**, *23*, 73–86. [[CrossRef](#)]
30. Demura, M. Challenges in Materials Integration. *ISIJ Int.* **2024**, *64*, 503–512. [[CrossRef](#)]

31. Mouratiadou, I.; Lemke, N.; Chen, C.; Wartenberg, A.; Bloch, R.; Donat, M.; Gaiser, T.; Basavegowda, D.H.; Helming, K.; Hosseini Yekani, S.A.; et al. The Digital Agricultural Knowledge and Information System (DAKIS): Employing Digitalisation to Encourage Diversified and Multifunctional Agricultural Systems. *Environ. Sci. Ecotechnology* **2023**, *16*, 100274. [[CrossRef](#)]
32. Tuzun, U. Artificial Intelligence Assisted Dynamic Control of Environmental Emissions From Hybrid Energy Process Plants (HEPP). *Front. Energy Res.* **2020**, *8*, 179. [[CrossRef](#)]
33. Pastor-Escuredo, D.; Treleven, P.; Vinuesa, R. An Ethical Framework for Artificial Intelligence and Sustainable Cities. *AI* **2022**, *3*, 961–974. [[CrossRef](#)]
34. Naseri, F.; Gil, S.; Barbu, C.; Cetkin, E.; Yarimca, G.; Jensen, A.C.; Larsen, P.G.; Gomes, C. Digital Twin of Electric Vehicle Battery Systems: Comprehensive Review of the Use Cases, Requirements, and Platforms. *Renew. Sustain. Energy Rev.* **2023**, *179*, 113280. [[CrossRef](#)]
35. Peng, X.; Li, Y.; Si, Y.; Xu, L.; Liu, X.; Li, D.; Liu, Y. A Social Sensing Approach for Everyday Urban Problem-Handling with the 12345-Complaint Hotline Data. *Comput. Env. Urban Syst.* **2022**, *94*, 101790. [[CrossRef](#)]
36. He, W. Urban Experiment: Taking Off on the Wind of AI. *Archit. Des.* **2020**, *90*, 94–99. [[CrossRef](#)]
37. Huang, Y.; Yang, S. Machine Learning Model for Building Type Classification of Cultural Heritage Sites along Jiangnan Canal: A Comparative Study of Historical and Modern Images. *Int. J. Des. Soc.* **2024**, *18*, 77–96. [[CrossRef](#)]
38. Liyanage, S.; Dia, H.; Abduljabbar, R.; Bagloee, S.A. Flexible Mobility On-Demand: An Environmental Scan. *Sustainability* **2019**, *11*, 1262. [[CrossRef](#)]
39. Beiró, M.G.; Panisson, A.; Tizzoni, M.; Cattuto, C. Predicting Human Mobility through the Assimilation of Social Media Traces into Mobility Models. *EPJ Data Sci.* **2016**, *5*, 30. [[CrossRef](#)]
40. Bernasconi, C.; Blume, L.B. Theorizing Architectural Research and Practice in the Metaverse: The Meta-Context of Virtual Community Engagement. *Int. J. Archit. Res. Archmet-IJAR* **2023**, *19*, 108–127. [[CrossRef](#)]
41. IDTA—Der Standard Für Den Digitalen Zwilling—Startseite. Available online: <https://industrialdigitaltwin.org/> (accessed on 29 April 2025).
42. Volz, F.; Sutschet, G.; Stojanovic, L.; Usländer, T. On the Role of Digital Twins in Data Spaces. *Sensors* **2023**, *23*, 7601. [[CrossRef](#)]
43. Cavalieri, S.; Gambadoro, S. Proposal of Mapping Digital Twins Definition Language to Open Platform Communications Unified Architecture. *Sensors* **2023**, *23*, 2349. [[CrossRef](#)]
44. Sun, H.; Liu, Z. Research on Intelligent Dispatching System Management Platform for Construction Projects Based on Digital Twin and BIM Technology. *Adv. Civ. Eng.* **2022**, *2022*, 1–19. [[CrossRef](#)]
45. Cakir, L.V.; Ozdem, M.; Ahmadi, H.; Canberk, B.; Duong, T.Q. Internet of Twins (IoTw) Approach: Digital Twin as a Platform (DTaaP) Architecture. *IEEE Internet Comput.* **2024**, *29*, 65–74. [[CrossRef](#)]
46. Chacón, R.; Casas, J.R.; Ramonell, C.; Posada, H.; Stipanovic, I.; Škarić, S. Requirements and Challenges for Infusion of SHM Systems within Digital Twin Platforms. *Struct. Infrastruct. Eng.* **2023**, *21*, 599–615. [[CrossRef](#)]
47. Rodríguez-Alonso, C.; Pena-Regueiro, I.; García, Ó. Digital Twin Platform for Water Treatment Plants Using Microservices Architecture. *Sensors* **2024**, *24*, 1568. [[CrossRef](#)]
48. Fawad, M.; Salamak, M.; Chen, Q.; Uscilowski, M.; Koris, K.; Jasinski, M.; Lazinski, P.; Piotrowski, D. Development of Immersive Bridge Digital Twin Platform to Facilitate Bridge Damage Assessment and Asset Model Updates. *Comput. Ind.* **2025**, *164*, 104189. [[CrossRef](#)]
49. Keskin, B.; Salman, B.; Koseoglu, O. Architecting a BIM-Based Digital Twin Platform for Airport Asset Management: A Model-Based System Engineering with SysML Approach. *J. Constr. Eng. Manag.* **2022**, *148*, 04022020. [[CrossRef](#)]
50. Li, H.; Zhang, R.; Zheng, S.; Shen, Y.; Fu, C.; Zhao, H. Digital Twin-Driven Intelligent Operation and Maintenance Platform for Large-Scale Hydro-Steel Structures. *Adv. Eng. Inform.* **2024**, *62*, 102661. [[CrossRef](#)]
51. Zhou, C.; Qin, W.; Luo, H.; Yu, Q.; Fan, B.; Zheng, Q. Digital Twin for Smart Metro Service Platform: Evaluating Long-Term Tunnel Structural Performance. *Autom. Constr.* **2024**, *167*, 105713. [[CrossRef](#)]
52. Dani, A.A.H.; Supangkat, S.H.; Lubis, F.F.; Nugraha, I.G.B.B.; Kinanda, R.; Rizkia, I. Development of a Smart City Platform Based on Digital Twin Technology for Monitoring and Supporting Decision-Making. *Sustainability* **2023**, *15*, 14002. [[CrossRef](#)]
53. Cho, Y.; Kim, S.; Lee, J.; Ko, D.; Lee, H.; Baek, Y.; Lee, M. Low-Cost Urban Heat Environment Sensing Device with Android Platform for Digital Twin. *HardwareX* **2024**, *20*, e00598. [[CrossRef](#)] [[PubMed](#)]
54. Lee, A.; Lee, K.W.; Kim, K.H.; Shin, S.W. A Geospatial Platform to Manage Large-Scale Individual Mobility for an Urban Digital Twin Platform. *Remote Sens.* **2022**, *14*, 723. [[CrossRef](#)]
55. Yang, S.; Kim, H. Urban Digital Twin Applications as a Virtual Platform of Smart City. *Int. J. Sustain. Build. Technol. Urban Dev.* **2021**, *12*, 363–379. [[CrossRef](#)]
56. Niccolucci, F.; Felicetti, A.; Hermon, S. Populating the Data Space for Cultural Heritage with Heritage Digital Twins. *Data* **2022**, *7*, 105. [[CrossRef](#)]
57. Turilazzi, B.; Leoni, G.; Gaspari, J.; Masari, M.; Boulanger, S.O.M. Cultural Heritage and Digital Tools: The Rock Interoperable Platform. *Int. J. Environ. Impacts* **2021**, *4*, 276–288. [[CrossRef](#)]

58. Li, C.; Lu, P.; Zhu, W.; Zhu, H.; Zhang, X. Intelligent Monitoring Platform and Application for Building Energy Using Information Based on Digital Twin. *Energies* **2023**, *16*, 6839. [[CrossRef](#)]
59. Han, F.; Du, F.; Jiao, S.; Zou, K. Predictive Analysis of a Building's Power Consumption Based on Digital Twin Platforms. *Energies* **2024**, *17*, 3692. [[CrossRef](#)]
60. Kolahi, M.; Esmailifar, S.M.; Moradi Sizkouhi, A.M.; Aghaei, M. Digital-PV: A Digital Twin-Based Platform for Autonomous Aerial Monitoring of Large-Scale Photovoltaic Power Plants. *Energy Convers. Manag.* **2024**, *321*, 118963. [[CrossRef](#)]
61. Banfi, F.; Brumana, R.; Salvalai, G.; Previtali, M. Digital Twin and Cloud BIM-XR Platform Development: From Scan-to-BIM-to-DT Process to a 4D Multi-User Live App to Improve Building Comfort, Efficiency and Costs. *Energies* **2022**, *15*, 4497. [[CrossRef](#)]
62. Qian, Y.; Leng, J.; Zhou, K.; Liu, Y. How to Measure and Control Indoor Air Quality Based on Intelligent Digital Twin Platforms: A Case Study in China. *Build. Environ.* **2024**, *253*, 111349. [[CrossRef](#)]
63. Goh, B.H.; Sun, Y. The Development of Life-Cycle Costing for Buildings. *Build. Res. Inf.* **2016**, *44*, 319–333. [[CrossRef](#)]
64. Choi, J.; Kim, H.; Kim, I. Open BIM-Based Quantity Take-off System for Schematic Estimation of Building Frame in Early Design Stage. *J. Comput. Des. Eng.* **2015**, *2*, 16–25. [[CrossRef](#)]
65. Zhang, Z.; Liu, H.; Xu, J.; Shu, Y.; Liu, H.; Xiao, J. Ontology-Based Integrated Cost Management System for Real Estate Development. In *ICCREM 2022: Carbon Peak and Neutrality Strategies of the Construction Industry*; American Society of Civil Engineers: Reston, VA, USA, 2022; Volume 2022, pp. 838–854. [[CrossRef](#)]
66. Li, C.Z.; Xue, F.; Li, X.; Hong, J.; Shen, G.Q. An Internet of Things-Enabled BIM Platform for on-Site Assembly Services in Prefabricated Construction. *Autom. Constr.* **2018**, *89*, 146–161. [[CrossRef](#)]
67. Wang, Y.; Lu, H.; Wang, Y.; Yang, Z.; Wang, Q.; Zhang, H. A Hybrid Building Information Modeling and Collaboration Platform for Automation System in Smart Construction. *Alex. Eng. J.* **2024**, *88*, 80–90. [[CrossRef](#)]
68. Hagedorn, P.; Pauwels, P.; König, M. Semantic Rule Checking of Cross-Domain Building Data in Information Containers for Linked Document Delivery Using the Shapes Constraint Language. *Autom. Constr.* **2023**, *156*, 105106. [[CrossRef](#)]
69. Yilmaz, S.; Kumar, D.; Hada, S.; Demirkesen, S.; Zhang, C.; Li, H. A PMBOK-Based Construction Cost Management Framework for BIM Integration in Construction Projects. *Int. J. Constr. Manag.* **2025**, *25*, 861–875. [[CrossRef](#)]
70. Hagedorn, P.; Liu, L.; König, M.; Hajdin, R.; Blumenfeld, T.; Stöckner, M.; Billmaier, M.; Grossauer, K.; Gavin, K. BIM-Enabled Infrastructure Asset Management Using Information Containers and Semantic Web. *J. Comput. Civ. Eng.* **2023**, *37*, 04022041. [[CrossRef](#)]
71. Katipamula, S.; Gowri, K.; Hernandez, G. An Open-Source Automated Continuous Condition-Based Maintenance Platform for Commercial Buildings. *Sci. Technol. Built Environ.* **2017**, *23*, 546–556. [[CrossRef](#)]
72. Li, X.; Lu, W.; Xue, F.; Wu, L.; Zhao, R.; Lou, J.; Xu, J. Blockchain-Enabled IoT-BIM Platform for Supply Chain Management in Modular Construction. *J. Constr. Eng. Manag.* **2021**, *148*, 04021195. [[CrossRef](#)]
73. Stas, S.; Abrishami, S. Decentralised Automated BIM Collaboration: A Blockchain and WBS Integrated Platform. *Smart Sustain. Built Environ.* **2024**; ahead of print. [[CrossRef](#)]
74. Yu, Z.; Sun, J. Green Cooperation Strategy of Prefabricated Building Supply Chain Based on Smart Construction Management Platform. *Sustainability* **2023**, *15*, 15882. [[CrossRef](#)]
75. Yang, J.; Zhong, B. Fairness Model Considering Satisfaction and Preferences for Service Scheduling on Electronic Platforms in Construction Industry. *Expert. Syst. Appl.* **2024**, *244*, 122872. [[CrossRef](#)]
76. Hu, H.; Huang, T.; Cheng, Y.; Lu, H. The Evolution of Sustainable Business Model Innovation: Evidence from a Sharing Economy Platform in China. *Sustainability* **2019**, *11*, 4207. [[CrossRef](#)]
77. Wu, Z. Application of Artificial Intelligence Technology in Smart Building Integrated Management Platform under Big Data Environment. *Appl. Math. Nonlinear Sci.* **2024**, *9*. [[CrossRef](#)]
78. Icoğlu, O.; Brunner, K.A.; Mahdavi, A.; Suter, G. A Distributed Location Sensing Platform for Dynamic Building Models. In *Ambient Intelligence. Proceedings of the European Symposium on Ambient Intelligence (EUSAI 2004), Eindhoven, The Netherlands, 8–11 November 2004*; Lecture Notes in Computer Science; Springer: Berlin/Heidelberg, Germany, 2004; Volume 3295, pp. 124–135. [[CrossRef](#)]
79. Mishchenko, V.; Lapidus, A.; Topchiy, D.; Kazakov, D. Organizational and Technological Platform for Monolithic Construction Using Pneumatic Formwork. *Civ. Eng. J.* **2023**, *9*, 2787–2795. [[CrossRef](#)]
80. Wu, N.; Shih, S.G. A BIM Inspired Supporting Platform for Architectural Design. *Comput. Aided Des. Appl.* **2015**, *12*, 327–337. [[CrossRef](#)]
81. Núñez, D.; Ferrada, X.; Neyem, A.; Serpell, A.; Sepúlveda, M. A User-Centered Mobile Cloud Computing Platform for Improving Knowledge Management in Small-to-Medium Enterprises in the Chilean Construction Industry. *Appl. Sci.* **2018**, *8*, 516. [[CrossRef](#)]
82. Gilbert, T.; Barr, S.; James, P.; Morley, J.; Ji, Q. Software Systems Approach to Multi-Scale GIS-BIM Utility Infrastructure Network Integration and Resource Flow Simulation. *ISPRS Int. J. Geoinf.* **2018**, *7*, 310. [[CrossRef](#)]
83. Howell, S.; Rezgui, Y.; Beach, T. Integrating Building and Urban Semantics to Empower Smart Water Solutions. *Autom. Constr.* **2017**, *81*, 434–448. [[CrossRef](#)]

84. Demir, S.; Yomralioglu, T. Bridging Geo-Data and Natural Gas Pipeline Design Standards: A Systematic Review of BIM-GIS Integration for Natural Gas Pipeline Asset Management. *Energies* **2024**, *17*, 2306. [[CrossRef](#)]
85. Azevedo, D.M.; Lamounier, E.; Guttler, C.; Marotti, A.; De Lima, G.F.M.; Rocha, R.D.O.; Cardoso, A.; De Araújo, A.L.; Bartholomeu, C. Development of BIM (Building Information Modeling) Concept Applied to Projects of Substations Integrated with the Geographic Intelligence System. *WSEAS Trans. Power Syst.* **2021**, *16*, 1–7. [[CrossRef](#)]
86. Wang, S.; Sun, Y.; Sun, Y.; Guan, Y.; Feng, Z.; Lu, H.; Cai, W.; Long, L. A Hybrid Framework for High-Performance Modeling of Three-Dimensional Pipe Networks. *ISPRS Int. J. Geoinf.* **2019**, *8*, 441. [[CrossRef](#)]
87. Zhao, L.; Liu, Z.; Mbachou, J. An Integrated BIM-GIS Method for Planning of Water Distribution System. *ISPRS Int. J. Geoinf.* **2019**, *8*, 331. [[CrossRef](#)]
88. Wang, X.; Huo, L.; Shen, T.; Yang, X.; Bai, H. A Web3D Rendering Optimization Algorithm for Pipeline BIM Models. *Buildings* **2023**, *13*, 2309. [[CrossRef](#)]
89. Marzouk, M.; Othman, A. Planning Utility Infrastructure Requirements for Smart Cities Using the Integration between BIM and GIS. *Sustain. Cities Soc.* **2020**, *57*, 102120. [[CrossRef](#)]
90. Rabia, R.M.P.; Kumar, S.D. BIM and GIS Integrated Utility Supply Station Location Optimization and Possibilities. *J. Appl. Eng. Sci.* **2022**, *20*, 184–1394. [[CrossRef](#)]
91. Zhang, S.; Hou, D.; Wang, C.; Pan, F.; Yan, L. Integrating and Managing BIM in 3D Web-Based GIS for Hydraulic and Hydropower Engineering Projects. *Autom. Constr.* **2020**, *112*, 103114. [[CrossRef](#)]
92. Lee, P.C.; Wang, Y.; Lo, T.P.; Long, D. An Integrated System Framework of Building Information Modelling and Geographical Information System for Utility Tunnel Maintenance Management. *Tunn. Undergr. Space Technol.* **2018**, *79*, 263–273. [[CrossRef](#)]
93. Wang, M.; Deng, Y.; Won, J.; Cheng, J.C.P. An Integrated Underground Utility Management and Decision Support Based on BIM and GIS. *Autom. Constr.* **2019**, *107*, 102931. [[CrossRef](#)]
94. Shekargoftar, A.; Taghaddos, H.; Azodi, A.; Nekouvaght Tak, A.; Ghorab, K. An Integrated Framework for Operation and Maintenance of Gas Utility Pipeline Using BIM, GIS, and AR. *J. Perform. Constr. Facil.* **2022**, *36*. [[CrossRef](#)]
95. Rajadurai, R.; Vilventhan, A. Integration of Building Information Modeling, Geographic Information System, and Augmented Reality for Visualization and Management of Multiple Underground Utilities. *J. Pipeline Syst. Eng. Pr.* **2025**, *16*. [[CrossRef](#)]
96. Lee, J.; Lee, Y.; Hong, C. Development of Geospatial Data Acquisition, Modeling, and Service Technology for Digital Twin Implementation of Underground Utility Tunnel. *Appl. Sci.* **2023**, *13*, 4343. [[CrossRef](#)]
97. Lee, J.; Lee, Y.; Park, S.; Hong, C. Implementing a Digital Twin of an Underground Utility Tunnel for Geospatial Feature Extraction Using a Multimodal Image Sensor. *Appl. Sci.* **2023**, *13*, 9137. [[CrossRef](#)]
98. Bansal, V.K. Integrated Framework of BIM and GIS Applications to Support Building Lifecycle: A Move toward ND Modeling. *J. Archit. Eng.* **2021**, *27*, 05021009. [[CrossRef](#)]
99. Ma, F.; Gao, Y.; Zhang, G.; Huang, C.; Chen, W. *An Underground Pipeline Relocation Decision Support System Based on BIM and GIS Integration*; Journal of Physics: Conference Series; IOP Publishing Ltd.: Bristol, UK, 2024; Volume 2824.
100. Huang, Y.; Peng, H.; Wen, L.; Xing, T. Using Digital Technologies to Plan and Manage the Pipelines Network in City. *IET Smart Cities* **2023**, *5*, 95–110. [[CrossRef](#)]
101. Huang, Y.; Peng, H.; Fang, X.; Xing, T. A Research on Data Integration and Application Technology of Urban Comprehensive Pipe Gallery Based on Three-Dimensional Geographic Information System Platform. *IET Smart Cities* **2023**, *5*, 111–122. [[CrossRef](#)]
102. Rajadurai, R.; Vilventhan, A. Integrating Road Information Modeling (RIM) and Geographic Information System (GIS) for Effective Utility Relocations in Infrastructure Projects. *Eng. Constr. Archit. Manag.* **2022**, *29*, 3647–3663. [[CrossRef](#)]
103. Sharafat, A.; Khan, M.S.; Latif, K.; Tanoli, W.A.; Park, W.; Seo, J. Bim-Gis-Based Integrated Framework for Underground Utility Management System for Earthwork Operations. *Appl. Sci.* **2021**, *11*, 5721. [[CrossRef](#)]
104. Kloppenburg, S.; Boekelo, M. Digital Platforms and the Future of Energy Provisioning: Promises and Perils for the next Phase of the Energy Transition. *Energy Res. Soc. Sci.* **2019**, *49*, 68–73. [[CrossRef](#)]
105. Canelón, R.; Peña, C.; Salazar, A. DINNP-U: A Design Process for Digital Innovation Platforms In Energy Sector Companies. *J. Technol. Manag. Innov.* **2022**, *17*. [[CrossRef](#)]
106. Li, P.; Cheng, K.; Jiang, P. Investigation on Quantitative Analysis of Carbon Footprint in Discrete Manufacturing by Using the Innovative Energy Dataspace Approach. *Manuf. Lett.* **2021**, *27*, 58–62. [[CrossRef](#)]
107. Duch-Brown, N.; Rossetti, F. Digital Platforms across the European Regional Energy Markets. *Energy Policy* **2020**, *144*, 111612. [[CrossRef](#)]
108. Bjørndal, E.; Bjørndal, M.; Kjerstad Bøe, E.; Dalton, J.; Guajardo, M. Smart Home Charging of Electric Vehicles Using a Digital Platform. *Smart Energy* **2023**, *12*, 100118. [[CrossRef](#)]
109. Heiden, P.z.; Priefer, J.; Beverungen, D. Predictive Maintenance on the Energy Distribution Grid-Design and Evaluation of a Digital Industrial Platform in the Context of a Smart Service System. *IEEE Trans. Eng. Manag.* **2024**, *71*, 3641–3655. [[CrossRef](#)]

110. Liu, B.; Penaka, S.R.; Lu, W.; Feng, K.; Rebbling, A.; Olofsson, T. Data-Driven Quantitative Analysis of an Integrated Open Digital Ecosystems Platform for User-Centric Energy Retrofits: A Case Study in Northern Sweden. *Technol. Soc.* **2023**, *75*, 102347. [[CrossRef](#)]
111. Patel, S.; Ghosh, A.; Ray, P.K. Optimum Control of Power Flow Management in PV, Wind, and Battery-Integrated Hybrid Microgrid Systems by Implementing in Real-Time Digital Simulator-Based Platform. *Soft Comput.* **2023**, *27*, 10863–10891. [[CrossRef](#)]
112. Li, B.; Zhao, H.; Gao, S.; Hu, S. Digital Real-Time Co-Simulation Platform of Refined Wind Energy Conversion System. *Int. J. Electr. Power Energy Syst.* **2020**, *117*, 105676. [[CrossRef](#)]
113. Wang, W.; Wang, L.; Zhu, B.; Li, G.; Xin, Y.; Jiang, S. Construction of a Digital and Physical Hybrid Simulation Platform for MMC-HVDC Grid With Fault Current Suppression Equipment. *Front. Energy Res.* **2021**, *9*, 660236. [[CrossRef](#)]
114. Zhou, K.; Yang, W.; Bai, H.; Liu, T.; Xu, M.; Yao, R.; Wu, L. Power Flow Control Strategy of Wind Power Hybrid Power Grid Based on Digital Simulation Cloud Platform Architecture. *REPQJ* **2024**, *22*, 76–84. [[CrossRef](#)]
115. Minuto, F.D.; Lanzini, A.; Giannuzzo, L.; Borchiellini, R. Digital Platforms for Renewable Energy Communities Projects: An Overview. *Int. J. Sustain. Dev. Plan.* **2022**, *17*, 2007–2013. [[CrossRef](#)]
116. Hill, M.; Duffy, A. A Digital Support Platform for Community Energy: One-Stop-Shop Architecture, Development and Evaluation. *Energies* **2022**, *15*, 4763. [[CrossRef](#)]
117. Abo-Khalil, A.G. Digital Twin Real-Time Hybrid Simulation Platform for Power System Stability. *Case Stud. Therm. Eng.* **2023**, *49*, 103237. [[CrossRef](#)]
118. Kovalyov, S.P. Distributed Energy Resources Management: From Digital Twin to Digital Platform. *IFAC-PapersOnLine* **2022**, *55*, 460–465. [[CrossRef](#)]
119. Kasper, L.; Birkelbach, F.; Schwarzmayr, P.; Steindl, G.; Ramsauer, D.; Hofmann, R. Toward a Practical Digital Twin Platform Tailored to the Requirements of Industrial Energy Systems. *Appl. Sci.* **2022**, *12*, 6981. [[CrossRef](#)]
120. Zhou, J.; Wei, J.; Xie, G.; Ran, L.; Zhang, Y. *Architecture Design of Digital Twin Platform for AC&DC Hybrid Transmission System with MMC-HVDC*; Journal of Physics: Conference Series; IOP Publishing Ltd.: Bristol, UK, 2021; Volume 1754.
121. De Rubeis, T.; Ciccozzi, A.; Ragnoli, M.; Stornelli, V.; Brusaporci, S.; Tata, A.; Ambrosini, D. A Workflow for a Building Information Modeling-Based Thermo-Hygrometric Digital Twin: An Experimentation in an Existing Building. *Sustainability* **2024**, *16*, 10281. [[CrossRef](#)]
122. Han, J.; Hong, Q.; Feng, Z.; Syed, M.H.; Burt, G.M.; Booth, C.D. Design and Implementation of a Real-Time Hardware-in-the-Loop Platform for Prototyping and Testing Digital Twins of Distributed Energy Resources. *Energies* **2022**, *15*, 6629. [[CrossRef](#)]
123. Savić, G.; Segedinac, M.; Konjović, Z.; Vidaković, M.; Dutina, R. Towards a Domain-Neutral Platform for Sustainable Digital Twin Development. *Sustainability* **2023**, *15*, 13612. [[CrossRef](#)]
124. Niet, I.A.; Dekker, R.; van Est, R. Seeking Public Values of Digital Energy Platforms. *Sci. Technol. Hum. Values* **2022**, *47*, 380–403. [[CrossRef](#)]
125. Bartczak, K. Digital Technology Platforms as an Innovative Tool for the Implementation of Renewable Energy Sources. *Energies* **2021**, *14*, 7877. [[CrossRef](#)]
126. Grytsenko, A.; Lypov, V.; Nosova, O. Cooperative Digital Platform in the Renewable Energy Sector. *Intellect. Econ.* **2024**, *18*, 214–230. [[CrossRef](#)]
127. Gago, D.; Mendes, P.; Murta, P.; Cabrita, N.; Teixeira, M.R. Stakeholders' Perceptions of New Digital Energy Management Platform in Municipality of Loulé, Southern Portugal: A SWOT-AHP Analysis. *Sustainability* **2022**, *14*, 1445. [[CrossRef](#)]
128. Komasilovs, V.; Bumanis, N.; Kviesis, A.; Anhorn, J.; Zacepins, A. Development of the Digital Matchmaking Platform for International Cooperation in the Biogas Sector. *Agron. Res.* **2021**, *19*, 809–818. [[CrossRef](#)]
129. Ferenz, S.; Ofenloch, A.; Penaherrera Vaca, F.; Wagner, H.; Werth, O.; Breitner, M.H.; Engel, B.; Lehnhoff, S.; Niefse, A. An Open Digital Platform to Support Interdisciplinary Energy Research and Practice—Conceptualization. *Energies* **2022**, *15*, 6417. [[CrossRef](#)]
130. Bartczak, K.; Łobejko, S. The Implementation Environment for a Digital Technology Platform of Renewable Energy Sources. *Energies* **2022**, *15*, 5793. [[CrossRef](#)]
131. Nakisbaev, D.; Dugalich, N. Introduction of Digital Platforms to State and Municipal Administration: Opportunities for Regulation and Transformation of Social Services for the Population | Introdução de Plataformas Digitais à Administração Estadual e Municipal: Oportunidades de Regu. *Rev. Bras. Políticas Públicas* **2022**, *12*, 133–143. [[CrossRef](#)]
132. Ansell, C.; Miura, S. Can the Power of Platforms Be Harnessed for Governance? *Public Adm.* **2020**, *98*, 261–276. [[CrossRef](#)]
133. Meijer, A.; Boon, W. Digital Platforms for the Co-Creation of Public Value. *Policy Polit* **2021**, *49*, 231–248. [[CrossRef](#)]
134. Janowski, T.; Estevez, E.; Baguma, R. Platform Governance for Sustainable Development: Reshaping Citizen-Administration Relationships in the Digital Age. *Gov. Inf. Q.* **2018**, *35*, S1–S16. [[CrossRef](#)]
135. Bellone, C.; Naselli, F.; Andreassi, F. New Governance Path through Digital Platforms and the Old Urban Planning Process in Italy. *Sustainability* **2021**, *13*, 6911. [[CrossRef](#)]

136. Gonçalves, J.E.; Ioannou, I.; Verma, T. No One-Size-Fits-All: Multi-Actor Perspectives on Public Participation and Digital Participatory Platforms. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* **2024**, *382*, 20240111. [[CrossRef](#)]
137. Falco, E.; Kleinhans, R. Digital Participatory Platforms for Co-Production in Urban Development: A Systematic Review. *Int. J. E-Plan. Res.* **2018**, *7*, 52–79. [[CrossRef](#)]
138. Secinaro, S.; Brescia, V.; Iannaci, D.; Jonathan, G.M. Does Citizen Involvement Feed on Digital Platforms? *Int. J. Public Adm.* **2022**, *45*, 708–725. [[CrossRef](#)]
139. Parkar, K. Digital Legacies and Distressed Capacities Evaluating Platforms of Spatial Governance in Bhubaneswar. *South Asia Multidiscip. Acad. J.* **2023**, *30*, 1–19.
140. De Blasio, E.; Selva, D. Implementing Open Government: A Qualitative Comparative Analysis of Digital Platforms in France, Italy and United Kingdom. *Qual. Quant.* **2019**, *53*, 871–896. [[CrossRef](#)]
141. Maretti, M.; Russo, V.; del Gobbo, E. Open Data Governance: Civic Hacking Movement, Topics and Opinions in Digital Space. *Qual. Quant.* **2021**, *55*, 1133–1154. [[CrossRef](#)]
142. Esposito, F.M. Platforming Public Administration: An Empirical Analysis on the Institutionalization of Digital Technologies. *Tecnoscienza* **2024**, *15*, 39–59. [[CrossRef](#)]
143. Lima, C.M.M.; de Sousa, T.P.; Cristóvam, J.S.S. Platform Government and Public Services in Law 14,129/2021: Considerations for a Proper Digital Transformation | Governo Por Plataforma e Serviços Públicos Na Lei N° 14.129/2021: Considerações Para Uma Transformação Digital Adequada. *A&C Rev. Direito Adm. Const.* **2023**, *23*, 157–174. [[CrossRef](#)]
144. Rotta, M.J.R.; Sell, D.; dos Santos Pacheco, R.C.; Yigitcanlar, T. Digital Commons and Citizen Coproduction in Smart Cities: Assessment of Brazilian Municipal e-Government Platforms. *Energies* **2019**, *12*, 2813. [[CrossRef](#)]
145. Agrawal, P.; Narain, R.; Ullah, I. Analysis of Barriers in Implementation of Digital Transformation of Supply Chain Using Interpretive Structural Modelling Approach. *J. Model. Manag.* **2019**, *15*, 297–317. [[CrossRef](#)]
146. Martinez Lagunas, A.J.; Nik-Bakht, M. Process Mining, Modeling, and Management in Construction: A Critical Review of Three Decades of Research Coupled with a Current Industry Perspective. *J. Constr. Eng. Manag.* **2024**, *150*, 1–23. [[CrossRef](#)]
147. Michelotto, F.; Joia, L.A. Organizational Digital Transformation Readiness: An Exploratory Investigation. *J. Theor. Appl. Electron. Commer. Res.* **2024**, *19*, 3283–3304. [[CrossRef](#)]
148. Lu, J.; Holubová, I. Multi-Model Databases: A New Journey to Handle the Variety of Data. *ACM Comput. Surv.* **2020**, *52*, 1–38. [[CrossRef](#)]
149. Pauwels, P.; McGlenn, K. *Buildings and Semantics—Data Models and Web Technologies for the Built Environment*; CRC Press: Boca Raton, FL, USA, 2022.
150. Höltgen, L.; Cleve, F.; Hagedorn, P. Implementation of an Open Web Interface for the Container-Based Exchange of Linked Building Data. In Proceedings of the 32nd Forum Bauinformatik, Darmstadt, Germany, 9–10 September 2021.
151. Kang, T.W.; Mo, Y. A Comprehensive Digital Twin Framework for Building Environment Monitoring with Emphasis on Real-Time Data Connectivity and Predictability. *Dev. Built Environ.* **2024**, *17*, 100309. [[CrossRef](#)]
152. Amarilli, F.; Amigoni, F.; Fugini, M.G.; Zarri, G.P. A Semantic-Rich Approach to IoT Using the Generalized World Entities Paradigm. *Manag. Web Things Link. Real. World Web* **2017**, *4*, 105–147. [[CrossRef](#)]
153. Tang, S.; Shelden, D.R.; Eastman, C.M.; Pishdad-Bozorgi, P.; Gao, X. A Review of Building Information Modeling (BIM) and the Internet of Things (IoT) Devices Integration: Present Status and Future Trends. *Autom. Constr.* **2019**, *101*, 127–139. [[CrossRef](#)]
154. Stöckner, M.; Brow, I.; Zwernemann, P.; Hajdin, R.; Schiffmann, F.; Blumenfeld, T.; König, M.; Liu, L.; Gavin, K. *Exchange and Exploitation of Data from Asset Management Systems Using Vendor Free Format*; Grafar: online, 2022.
155. Mohd Nawi, M.N.; Baluch, N.; Bahauddin, A.Y. Impact of Fragmentation Issue in Construction Industry: An Overview. *MATEC Web Conf.* **2014**, *15*, 01009. [[CrossRef](#)]
156. Lu, Q.; Xie, X.; James, H.; Kumarand, P.A.; Jennifer, S. From BIM Towards Digital Twin: Strategy and Future Development for Smart Asset Management. In Proceedings of the Service Oriented, Holonic and Multi-Agent Manufacturing Systems for Industry of the Future; Borangiu, T., Trentesaux, D., Leitão, P., Legat, C., Eds.; Springer International Publishing: Cham, Switzerland, 2020; pp. 392–404.
157. Liu, L.; Zeng, N.; Liu, Y.; Han, D.; König, M. Multi-Domain Data Integration and Management for Enhancing Service-Oriented Digital Twin for Infrastructure Operation and Maintenance. *Dev. Built Environ.* **2024**, *18*, 100475. [[CrossRef](#)]
158. Akroyd, J.; Bhave, A.; Kraft, M.; Mosbach, S. Universal Digital Twin—A Dynamic Knowledge Graph. *Data-Centric Eng.* **2021**, *2*, e14. [[CrossRef](#)]
159. Semeraro, C.; Lezoche, M.; Panetto, H.; Dassisti, M. Digital Twin Paradigm: A Systematic Literature Review. *Comput. Ind.* **2021**, *130*, 103469. [[CrossRef](#)]
160. Soleimani, M.; Campean, F.; Neagu, D. Diagnostics and Prognostics for Complex Systems: A Review of Methods and Challenges. *Qual. Reliab. Eng. Int.* **2021**, *37*, 3746–3778. [[CrossRef](#)]
161. Grieves, M. DIKW as a General and Digital Twin Action Framework: Data, Information, Knowledge, and Wisdom. *Knowledge* **2024**, *4*, 120–140. [[CrossRef](#)]

162. Binni, L.; Brunetti, A.; Gara, F.; Naticchia, B. Bayesian Networks for Data Contextualization in Digital Twins of Complex Civil Infrastructures. In Proceedings of the 42st International Symposium on Automation and Robotics in Construction, Montreal, QC, Canada, 28–31 July 2025.
163. Galaz, V.; Centeno, M.A.; Callahan, P.W.; Causevic, A.; Patterson, T.; Brass, I.; Baum, S.; Farber, D.; Fischer, J.; Garcia, D.; et al. Artificial Intelligence, Systemic Risks, and Sustainability. *Technol. Soc.* **2021**, *67*, 101741. [[CrossRef](#)]
164. Shailesh Kulkarni, R.R.Y.N.C.B.M.P.K.M.C.B. AI-Driven Energy Management Systems for Smart Buildings. *Power Syst. Technol.* **2024**, *48*, 322–337. [[CrossRef](#)]
165. Kaewunruen, S.; O’Neill, C.; Sengsri, P. Digital Twin-Driven Strategic Demolition Plan for Circular Asset Management of Bridge Infrastructures. *Sci. Rep.* **2025**, *15*, 10554. [[CrossRef](#)]
166. Grieves, M. Intelligent Digital Twins and the Development and Management of Complex Systems. *Digit. Twin* **2022**, *2*, 8. [[CrossRef](#)]
167. Grieves, M.; Vickers, J. Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems. In *Transdisciplinary Perspectives on Complex Systems: New Findings and Approaches*; Kahlen, F.-J., Flumerfelt, S., Alves, A., Eds.; Springer International Publishing: Cham, Switzerland, 2017; pp. 85–113. ISBN 978-3-319-38756-7.
168. Luiten, B.; Böhms, M.; Alsem, D.; O’Keeffe, A. Asset Information Management Using Linked Data for the Life-Cycle of Roads. In *Life Cycle Analysis and Assessment in Civil Engineering: Towards an Integrated Vision. Proceedings of the 6th International Symposium on Life-Cycle Civil Engineering, IALCCE 2018, Ghent, Belgium, 28–31 October 2018*; Caspeepe, R., Taerwe, L., Frangopol, D., Eds.; CRC Press: Boca Raton, FL, USA, 2018; pp. 1529–1536.
169. Chamari, L.; Petrova, E.; Pauwels, P. An End-to-End Implementation of a Service-Oriented Architecture for Data-Driven Smart Buildings. *IEEE Access* **2023**, *11*, 117261–117281. [[CrossRef](#)]
170. Ramonell, C.; Chacón, R.; Posada, H. Knowledge Graph-Based Data Integration System for Digital Twins of Built Assets. *Autom. Constr.* **2023**, *156*, 105109. [[CrossRef](#)]
171. Göbels, A.; Beetz, J. Conversion of Legacy Domain Models into Ontologies for Infrastructure Maintenance. In Proceedings of the 9th Linked Data in Architecture and Construction Workshop, Luxembourg, 11–13 October 2021; Poveda-Villalón, M., Pauwels, P., Eds.; pp. 20–31.
172. Zhang, R.; El-Gohary, N. Hierarchical Representation and Deep Learning-Based Method for Automatically Transforming Textual Building Codes into Semantic Computable Requirements. *J. Comput. Civ. Eng.* **2022**, *36*, 04022022. [[CrossRef](#)]
173. Binni, L.; Vaccarini, M.; Spegni, F.; Messi, L.; Naticchia, B. An Automatic Registration System Based on Augmented Reality to Enhance Civil Infrastructure Inspections. *Buildings* **2025**, *15*, 1146. [[CrossRef](#)]
174. Messi, L.; Spegni, F.; Vaccarini, M.; Corneli, A.; Binni, L. Seamless Augmented Reality Registration Supporting Facility Management Operations in Unprepared Environments. *J. Inf. Technol. Constr.* **2024**, *29*, 1156–1180. [[CrossRef](#)]
175. Plevris, V.; Lagaros, N.D.; Zeytinci, A. Blockchain in Civil Engineering, Architecture and Construction Industry: State of the Art, Evolution, Challenges and Opportunities. *Front. Built Env.* **2022**, *8*, 840303. [[CrossRef](#)]
176. Jang, K.; Kim, J.-W.; Ju, K.-B.; An, Y.-K. Infrastructure BIM Platform for Lifecycle Management. *Appl. Sci.* **2021**, *11*, 10310. [[CrossRef](#)]
177. Pearl, J. *Probabilistic Reasoning in Intelligent Systems: Networks of Plausible Inference*; Morgan Kaufmann Publishers Inc.: San Francisco, CA, USA, 1988; ISBN 1558604790.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.