

Integrating BIM and AI For Smart Energy Systems: A Lean Construction Approach to Developing Sustainable and Resilient Infrastructure

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DOI: [10.22178/pos.125-20](https://doi.org/10.22178/pos.125-20)

LCC Subject Category: T1-995

Received 27.11.2025

Accepted 27.12.2025

Published online 31.12.2025

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Abstract. The construction industry faces unprecedented challenges in fulfilling its role in building sustainable, resilient infrastructure while managing growing complexity and resource constraints. This article discusses how the Building Information Model (BIM), artificial intelligence (AI), and Lean Construction principles are synergistically integrated to optimise innovative energy systems in a building environment. Through a wide-ranging review of the latest literature and case studies, this paper shows how, with the confluence of these technologies, predictive energy management, waste reduction, and better decision-making can be achieved across the project lifecycle. The results show that integrated BIM-AI frameworks can save 20-35% in energy use, reduce construction waste by up to 30%, and deliver projects 25-40% more efficiently. This research adds to the growing body of knowledge on digital transformation in construction, offering valuable insights for industry practitioners seeking to implement sustainable solutions in the infrastructure sector.

Keywords: Building Information Modelling; Artificial Intelligence; Lean Construction; Smart Energy Systems; Sustainable Infrastructure; Digital Twins.

INTRODUCTION

The global construction industry is responsible for approximately 38% of all energy-related CO₂ emissions and accounts for almost 36% of final energy worldwide [1]. As urbanisation continues to accelerate and climate imperatives become more urgent, the industry needs to change its approach to infrastructure development. The integration of digital technologies - especially the use of Building Information Modelling (BIM) and Artificial Intelligence (AI) - with Lean Construc-

tion methodologies is an interesting avenue for sustainable and resilient infrastructures [2].

BIM has moved beyond a 3D visualisation tool to become a complete lifecycle asset management platform, enabling collaborative design, construction, and optimisation of operations [3]. Concurrently, Artificial intelligence technological projects, such as machine learning and deep learning, along with neural networks, have become significant drivers of pattern recognition, predictive analytics, and autonomous decision-making [4]. When combined with Lean Construction principles, which focus on value maximisation

and waste minimisation, these technologies form a powerful system for developing innovative energy systems [5].

Intelligent energy systems are an evolution in comparison to the existing system for building services where they include smart sensors, tolerant controls, the integration of renewable energies and the optimisation in real-time, in order not to bring negative impacts to the environment, but on the other hand, to minimise for the occupant the consumption as far as bodily comfort and the benefits, ensuring the most significant levels of efficiency in the services [6]. The integration of BIM, AI, and Lean methodologies is enabling unprecedented capabilities, including energy prediction, performance optimisation, and continuous improvement across the building lifecycle.

This article explores the integrated use of BIM, AI, and Lean Construction to transform the development of intelligent energy systems to answer the following three major research questions:

- 1) How can BIM-AI integration improve the design and performance of energy systems?
- 2) What part do Lean principles play in optimising the implementation of digital technology?
- 3) What are frameworks and best practises for successful integration for sustainable infrastructure development?

Literature Review

1) Building Information Modelling Evolution. BIM has undergone a long journey since its development, evolving from 3D geometric modelling capabilities to nD applications such as time (4D), cost (5D), sustainability (6D), and facility management (7D) [7]. Recent developments in BIM technology have focused on interoperability, cloud-based collaboration, and applications that use Internet of Things (IoT) sensors for real-time data acquisition [8].

Contemporary BIM platforms are virtual prototypes of physical asset models that can be used to simulate, analyse, and optimise various aspects of a project throughout its lifecycle [9]. This capability is helpful in the design of an energy system, where multiple variables interact dynamically. Studies show that optimising energy consumption through BIM-enabled energy analysis

during design phases can yield energy savings of 15-25% compared with earlier methods [10].

2) Artificial Intelligence in Construction. AI applications in construction have grown explosively and now include computer vision to track project progress, machine learning to forecast project schedules, natural language processing to analyse contracts, and optimisation algorithms to manage resource allocation [11]. For energy systems specifically, AI has a knack for handling large datasets generated by building sensors, weather stations, and occupancy patterns, for instance, to develop predictive models and an adaptive approach [12].

Deep learning neural networks have shown excellent accuracy in predicting building energy consumption. Some deep learning models have been able to predict building energy consumption with a prediction error of less than 5% [13].

Reinforcement learning algorithms can optimise HVAC system operation in real time based on changing conditions, while minimising energy consumption and maintaining comfort parameters.

Reinforcement learning algorithms can optimise HVAC system operations in real time, adapting to changing conditions while avoiding energy waste and maintaining comfort parameters [14]. Generative AI tools now help designers test energy-efficient design alternatives and automatically generate and evaluate thousands of designs against specific performance requirements [16].

3) Lean Construction Principles. Lean Construction, which applies the principles of Lean thinking, initially used for manufacturing processes, to construction processes with a focus on value stream mapping, pull planning, last planner system and continuous improvement [16]. The basic assumption focuses on maximising value delivery and systematically eliminating all types of waste: overproduction, waiting time, transportation, over-processing, inventory, motion, and defects [17].

Recent studies have shown strong synergies between Lean and digital technologies. BIM is a tool that can enable Lean implementation through visual management, clash detection, and collaborative planning [18]. With the incorporation of AI-based analytics, Lean methodologies tend to become more data-driven and predictive, rather than reactive [19]. This integration has been highly effective in optimising the energy system,

leveraging Lean principles to identify waste and BIM-AI tools to enable analytical capabilities for systematic improvement.

4) Smart Energy Systems. Obama explains it in his blog: Smart energy systems bring together renewable energy sources, energy storage, advanced controls, and demand response capabilities to build adaptive, efficient, and resilient infrastructure [20]. These systems use sensor networks, building automation, and analytics platforms that continuously refine performance based on real-time conditions [21].

The complexity of modern energy systems, with the integration of solar photovoltaics, heat pumps, battery storage, electric vehicle charging, and grid connection, requires advanced modelling and optimisation methods [22]. BIM provides a geometric and parametric basis for the energy modelling system, while artificial intelligence (AI) algorithms can optimise operational systems and forecast maintenance needs [23].

METHOD

Research Framework. This research uses a mixed-methods approach, including a systematic literature review, a framework, and case study analysis. The literature review included peer-reviewed

articles published between 2023 and 2025 from major construction and energy journals, conference proceedings, and industry reports. Search terms were combinations of "BIM," "artificial intelligence," "machine learning," "Lean Construction," "smart energy," "sustainable infrastructure," and others in the field.

RESULTS AND DISCUSSION

Integration Framework Development. Based on a synthesis of the literature and best manufacturing practices, the authors developed a comprehensive framework for integrating BIM, AI, and Lean Construction in innovative energy system development. This framework identifies key touchpoints, data flows, and decision nodes across the stages of a project, from conception through operations.

BIM-AI-Lean Integration Framework

1) Framework Architecture. The proposed integration framework has five general layers: 1) Data Acquisition and Management; 2) Modelling and Simulation; 3) Analysis and Optimisation; 4) Implementation and Control; 5) Monitoring and Continuous Improvement (Table 1).

Table 1 – Integration Framework Components

Layer	BIM Functions	AI Applications	Lean Principles	Key Outputs
Data Acquisition	Geometric modelling, parameter definition, IoT integration	Sensor data processing, image recognition, data cleaning	Value stream identification, waste recognition	Comprehensive digital asset database
Modeling & Simulation	3D/nD modelling, energy simulation, clash detection	Generative design, scenario generation, digital twin creation	Pull planning, collaborative design	Optimised design alternatives
Analysis & Optimization	Performance analysis, lifecycle assessment, parametric studies	Machine learning predictions, neural network optimisation, pattern recognition	Root cause analysis, 5-Why technique	Data-driven recommendations
Implementation & Control	4D/5D scheduling, progress tracking, quality assurance	Computer vision monitoring, resource optimisation, automated reporting	Last Planner System, visual management	Real-time project control
Monitoring & Improvement	Facility management, asset tracking, performance monitoring	Predictive maintenance, anomaly detection, adaptive controls	Kaizen, PDCA cycles, continuous feedback	Operational optimisation

2) Design Phase Integration. During design phases, BIM serves as the central repository of geometric and semantic information about energy

systems, including equipment specifications, spatial relationships, and performance parameters (Figure 2, conceptual representation). AI algo-

rithms analyse this data, along with climate data, occupancy patterns, and utility rates, to develop optimised system configurations [4].

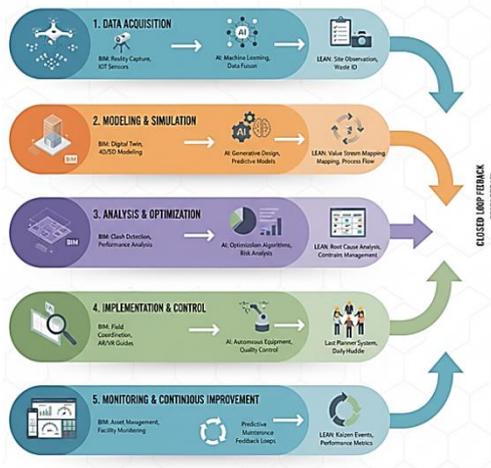


Figure 1 – Integrated Project



Figure 2 – Design Phase Integration

Lean principles support this process through set-based design, where many design alternatives are created and tested together before reaching optimal designs [3]. Value stream mapping to identify critical energy flows and potential sources of waste, and target value design to ensure that performance goals drive decisions rather than first-cost minimisation.

A futuristic 3D render of a smart energy-efficient building overlaid with a glowing digital twin model. Include holographic elements like data streams, IoT sensor icons, solar panels, and HVAC flow visualisations. The AI system monitors energy consumption through real-time analytics—using a realistic, high-tech, clean architectural visualisation style.

Generative design algorithms explore thousands of design permutations, automatically testing energy performance, cost implications, and construction constraints [15]. Machine learning models trained on historical data on building performance, when applied to these structures, predict energy consumption in operation with increasing accuracy, allowing designers to make data-driven decisions early, when changes are less costly [13].

3) Construction Phase of Integration. Construction execution benefits significantly from integrating BIM, AI, and Lean, thereby improving planning, monitoring, and quality control. 4D BIM Models: Level 4D models connected to the project schedule enable pull planning sessions, where trade contractors jointly schedule the flow of work to achieve the most efficient flow and reduce waiting times [18]. AI-powered schedule risk analysis helps identify the likelihood of delays and resource conflicts before they occur [11].

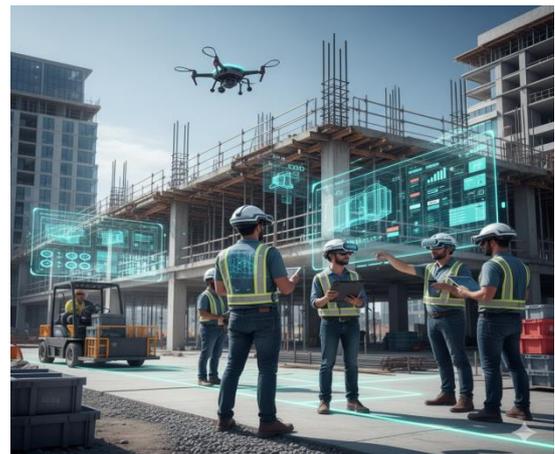


Figure 3 – Construction Phase of Integration

A construction site using digital tablets and AR headsets, with BIM 3D holograms projected over real structures. Workers coordinate around a digital planboard, with drones and robotic equipment optimising workflow. Highlight lean principles like visual management and just-in-time delivery—photorealistic, daylight setting, with futuristic touches.

Computer vision systems automatically monitor construction progress by comparing as-built conditions with BIM models to identify deviations and quality issues [8]. This real-time feedback allows for quick correction of the situation, which is the principle of Lean (to build quality

into processes instead of checking quality afterwards). Automated progress tracking lessens administrative burden and gets accurate data for earned value analysis and predictive completion forecasting.

For energy systems specifically, BIM enables accurate installation in line with the design intent, with augmented reality applications guiding technicians through complex assemblies [9]. Quality verification using digital checklists and photographic documentation provides comprehensive commissioning records, enabling a more seamless handover to operations teams.

4) Operations Phase Integration. The operations phase realises the potential of BIM-AI-Lean integration through continuously synchronised digital twins with physical building systems. IoT sensors across energy systems generate and feed real-time data to AI analytics platforms, enabling the identification of anomalies and equipment failures and the application of control techniques [21].

Machine learning algorithms examine patterns in energy use, weather conditions, occupancy levels, and equipment monitoring performance to build predictive models that enable proactive,

not reactive, management [14]. Reinforcement learning controllers continuously optimise HVAC operation, adjusting setpoints and staging equipment to minimise energy consumption and ensure comfort [12].

Lean's philosophy of continuous improvement is reflected in the frequency with which performance reviews compare actual energy consumption with BIM predictions and industry benchmarks [5]. Root cause analysis of performance gaps reveals the opportunities for system tuning, operational changes or capital upgrades. PDCA (Plan-Do-Check-Act) cycles effectively and systematically set up and prove improvements to build a culture of ongoing improvement.

Implementation Benefits and Challenges

1) Performance Improvements. Research and case studies have shown significant impacts of the combined use of BIM-AI-Lean approaches (Table 2). Energy performance improvements of 20-35% are achieved compared with conventional design and construction methods [10]. A 25-30% reduction in construction waste is achieved through better planning, clash detection, and just-in-time delivery enabled by BIM-Lean integration [17].

Table 2 – Documented Performance Improvements from BIM-AI-Lean Integration

Performance Metric	Improvement Range, %	Primary Contributing Factors	Source
Energy consumption reduction	20-35	AI optimisation, predictive controls, and BIM simulation accuracy	[6, 10]
Construction waste reduction	25-30	Clash detection, pull planning, and accurate quantity takeoffs	[17, 18]
Project schedule compression	15-25	4D planning, AI risk prediction, Lean workflow optimisation	[11, 19]
Cost savings	10-20	Early issue detection, optimised resource allocation, reduced rework	[2, 7]
Maintenance cost reduction	20-30	Predictive maintenance, digital twin monitoring, automated diagnostics	[9, 14]
Design time reduction	30-40	Generative design, automated analysis, parametric modelling	[4, 15]

Project schedule improvements of 15-25% emerge from enhanced planning, reduced rework, and optimised sequencing [11]. Overall cost savings of 10-20% result from early issue detection, reduced change orders, and improved resource utilisation [2]. Maintenance costs during operations decrease 20-30% through predictive rather than reactive approaches [9].

2) Implementation Challenges. Despite compelling benefits, organisations face significant challenges in implementing integrated BIM-AI-Lean approaches (Table 3). Technical barriers such as data interoperability issues across platforms, inefficient computational infrastructure for AI processing, and cybersecurity problems in connected building systems [23].

Table 3 – Implementation Challenges and Mitigation Strategies

Challenge Category	Specific Barriers	Mitigation Strategies	Critical Success Factors
Technical	Data interoperability, computational requirements, and integration complexity	Open standards (IFC), cloud computing, API development	Robust IT infrastructure, technical expertise
Organisational	Resistance to change, siloed workflows, inadequate collaboration	Change management, cross-functional teams, executive sponsorship	Leadership commitment, collaborative culture
Skills & Training	Knowledge gaps, limited AI expertise, and BIM proficiency deficits	Training programs, partnerships with academia, and mentoring	Continuous learning investment, skill development
Financial	High initial investment, uncertain ROI, and budget constraints	Phased implementation, pilot projects, value demonstration	Long-term perspective, performance metrics
Process	Fragmented project delivery, contractual barriers, and risk allocation	Integrated project delivery, BIM execution plans, and clear protocols	Aligned incentives, shared risk-reward
Data Quality	Incomplete data, sensor accuracy issues, data governance gaps	Data validation protocols, quality assurance, standardisation	Data management policies, accountability

Organisational barriers are also found to be equally relevant, such as resistance to change, isolated project delivery approaches, and poor collaboration between disciplines [16]. Traditional contractual arrangements tend to misalign incentives, leading to hesitation to invest in and share information for successful integration [19].

Skills gaps are a crucial limitation, as very few professionals are familiar with the different areas of BIM, AI, and Lean methodologies [5]. Educational programmes have been slow to align curricula with the workforce development challenges. Expensive initial investment costs and uncertain investment return timelines again hinder completion, especially for smaller organisations [20].

3) Success Factors. Successful implementations share several characteristics. Strong executive sponsorship and organisational commitment to digital transformation are key to this, as integration entails a long-term investment and cultural change [2]. Early pilot projects with real gains go a long way toward building momentum and justification for broader deployment [18].

Collaborative project delivery methods, particularly Integrated Project Delivery (IPD) and alliance contracting, help align the incentives of different project stakeholders and facilitate the information sharing required for BIM-AI-Lean integration [3]. Clear BIM execution plans, data management protocols, and Artificial Intelligence

governance frameworks can set expectations and accountability [8].

Investment in workforce development through training, certifications, and partnerships with academic institutions creates organisational capability [7]. Beginning by focusing on specific applications, such as energy optimisation or progress monitoring, rather than on complete transformation, enables organisations to build eras in stages that support their value.

Case Applications and Industry Examples

1) Commercial Office Development. A recent commercial office project in Singapore has made significant strides in integrating BIM with AI and Lean to develop innovative energy systems [6]. During design, Generative Artificial Intelligence (AI) algorithms generated 5,000 design alternatives, optimising building orientation, envelope performance, and HVAC configuration. The chosen design achieved 32% reductions in energy compared to baseline code requirements.

Construction using 4D BIM pull planning integrated with artificial intelligence to optimise the schedule, 18% shorter, yet maintaining quality standards. Computer vision systems tracked MEP installation accuracy and flagged and adjusted 127 deviations that might otherwise have cost the processor money as rework. Lean daily huddles were used to quickly resolve coordination issues, with BIM as the visual management platform.

Upon completion, the building's digital twin will integrate data from 2400 IoT sensors. Machine learning algorithms are used to optimise chiller plant operations, saving an additional 22% of cooling energy compared with conventional control systems. Predictive models of maintenance in equipment - they forecast a 2–3-week window for the equipment to fail, allowing the system to reduce unplanned downtimes by 85% [6].

2) Healthcare Infrastructure. A significant hospital expansion project in the United Kingdom used BIM-AI-Lean integration to optimise complex energy systems serving critical care environments [22]. The project required redundant mechanical systems, accurate environmental controls, and 24/7 reliability, with low operational costs and carbon emissions.

BIM-based energy modelling identified opportunities to pursue combined heat and power systems, heat recovery, and thermal storage to achieve 28% energy savings. AI algorithms optimised the control sequences for these interdependent systems to balance competing requirements for efficiency, redundancy, and comfort. Lean value stream mapping eliminated 15% of the initially planned equipment by identifying duplicative capabilities.

During the construction process, lean last-planner system sessions simplified the complex choreography of mechanical installations compared with that of clinical equipment locations and infection control needs. BIM clash checking avoided 234 clashes that would have caused delays in clogged ceiling spaces, a typical issue in healthcare facilities. The project finished 12% ahead of schedule and generated 22% less construction waste than similar projects [22].

Future Directions and Emerging Technologies

1) Advanced AI Applications. Emerging abilities of Artificial intelligence promise to further advance the use of BIM for intelligent energy systems. Federated learning approaches help AI models improve by learning from multiple data sources without compromising privacy [12]. This collective intelligence speeds up the development of the model and the optimisation of algorithms. Large language models (LLMs) are being adapted for construction use, including natural language interfaces for BIM queries, automated code-compliance checking, and intelligent design assistance [15]. These are some of the tools that democratise access to complex analytics and en-

able professionals who are not necessarily data scientists to leverage AI capabilities.

While still an emerging sector, quantum computing has the potential to address complex energy system design optimisation problems that classical computers cannot solve [4]. As quantum hardware matures, it may enable optimising the building portfolio in real time based on grid limitations, energy markets, and occupant preferences.

2) Enhanced Integration Platforms. Next-generation platforms are coming to market that natively integrate BIM with AI and operational data, creating consolidated environments. These everyday data environments (CDEs) eliminate data silos and manual transfers, which currently limit the effectiveness of integration [23]. Blockchain technologies can increase data integrity and facilitate trusted data sharing across organisational boundaries [10]. Extended reality (XR) technologies, such as virtual reality (VR), augmented reality (AR), and mixed reality (MR), are developing immersive interfaces for interacting with BIM-AI systems [8]. Technicians can see energy flows, spot inefficiencies, and receive guided maintenance directions on the physical equipment through AR headsets.

3) Sustainability and Resilience. Future development will focus more on climate resilience and energy efficiency. BIM-AI integration enables the analysis of the impact of climate change on building performance, as well as the development of vulnerability and adaptation strategies [20]. AI algorithms can optimise systems across multiple objectives, such as carbon emissions, water consumption, material circularity, and ecosystem impacts.



Figure 4 – Sustainability and Resilience

A panoramic view of a sustainable smart city with interconnected energy-efficient buildings, solar rooftops, wind turbines, and electric vehicles. Data lines and AI analytics visual overlays connect infrastructure through a digital energy management network. Vibrant blue-green colour scheme, emphasising sustainability and clean energy technology.

Integration with energy models at the urban scale and with smart grid infrastructure will enable buildings' participation in demand response programs, vehicle-to-grid systems, and virtual power plants [21]. This integration of the building with the grid is enabling new opportunities for further optimisation and revenue generation while improving grid stability.

CONCLUSIONS

The merging of Building Information Modelling, Artificial Intelligence, and Lean Construction tenets is a revolutionary way to understand how to work in constructing intelligent, sustainable energy. This synthesis draws on the value-added advantages of each methodology: BIM's end-to-end digital representation and collaboration tool; AI's analytical and predictive capabilities; and Lean's focus on value creation and waste elimination.

Evidence from recent literature and case studies shows significant performance improvements across multiple dimensions. Energy consumption reductions of 20-35%, construction waste reductions of 25-30%, schedules compressed by 15-

25%, and maintenance costs reduced by 20-30% are good reasons to invest in integrated approaches. These benefits continue throughout the project lifecycle from optimising design to operational excellence.

Successful implementation involves considering technical, organisational, and skills-related issues through strategic approaches such as executive sponsorship, cooperative delivery methods, workforce development, and phased implementation. Organisations should try small pilot projects focused on demonstrating value, while they build organisational capabilities - one project at a time.

The trajectory of technological development implies that the BIM-AI-Lean combination will become mainstream practise, not an innovative exception, as the pace of digital transformation accelerates throughout the construction industry. Emerging technologies such as federated learning, quantum computing, extended reality, and enhanced integration platforms will further increase the benefits of integration.

As climate imperatives are stepped up a notch, along with infrastructure requirements, the time is for the construction industry to adopt these digital methodologies to deliver the sustainable, efficient and resilient infrastructure the world needs. BIM-AI-Lean integration offers a framework that provides a proven solution to these challenges while creating value for all stakeholders throughout the lifecycle of the built environment.

REFERENCES

1. International Energy Agency. (2023). Buildings: Tracking report. Retrieved from <https://www.iea.org/energy-system/buildings>
2. Saka, A. B., & Chan, D. W. M. (2019). A Scientometric Review and metasynthesis of Building Information Modelling (BIM) research in Africa. *Buildings*, 9(4), 85. doi: [10.3390/buildings9040085](https://doi.org/10.3390/buildings9040085)
3. Gao, H., Koch, C., & Wu, Y. (2019). Building information modelling-based building energy modelling: A review. *Applied Energy*, 238, 320–343. doi: [10.1016/j.apenergy.2019.01.032](https://doi.org/10.1016/j.apenergy.2019.01.032)
4. Liu, Z., Jiang, L., Osmani, M., & Demian, P. (2019). Building Information Management (BIM) and Blockchain (BC) for Sustainable Building Design Information Management Framework. *Electronics*, 8(7), 724. doi: [10.3390/electronics8070724](https://doi.org/10.3390/electronics8070724)
5. Amuda-Yusuf, G. (2018). Critical success factors for building Information modelling Implementation. *Construction Economics and Building*, 18(3), 55–73. doi: [10.5130/ajceb.v18i3.6000](https://doi.org/10.5130/ajceb.v18i3.6000)
6. Wang, Z., & Srinivasan, R. S. (2015). A review of artificial intelligence-based building energy prediction with a focus on ensemble prediction models. *Winter Simulation Conference (WSC)*, 3438–3448. doi: [10.1109/wsc.2015.7408504](https://doi.org/10.1109/wsc.2015.7408504)

7. Olawumi, T. O., & Chan, D. W. M. (2020). Green-building information modelling (Green-BIM) assessment framework for evaluating sustainability performance of building projects: a case of Nigeria. *Architectural Engineering and Design Management*, 17(5–6), 458–477. doi: [10.1080/17452007.2020.1852910](https://doi.org/10.1080/17452007.2020.1852910)
8. Chen, K., Lu, W., Peng, Y., Rowlinson, S., & Huang, G. Q. (2015). Bridging BIM and building: From a literature review to an integrated conceptual framework. *International Journal of Project Management*, 33(6), 1405–1416. doi: [10.1016/j.ijproman.2015.03.006](https://doi.org/10.1016/j.ijproman.2015.03.006)
9. Khajavi, S. H., Motlagh, N. H., Jaribion, A., Werner, L. C., & Holmstrom, J. (2019). Digital Twin: vision, benefits, boundaries, and creation for buildings. *IEEE Access*, 7, 147406–147419. doi: [10.1109/access.2019.2946515](https://doi.org/10.1109/access.2019.2946515)
10. Gao, H., Zhang, L., Koch, C., & Wu, Y. (2019). BIM-based real-time building energy simulation and optimisation in the early design stage. *IOP Conference Series Materials Science and Engineering*, 556(1), 012064. doi: [10.1088/1757-899x/556/1/012064](https://doi.org/10.1088/1757-899x/556/1/012064)
11. Darko, A., Chan, A. P., Yang, Y., & Tetteh, M. O. (2020). Building information modelling (BIM)-based modular integrated construction risk management – Critical survey and future needs. *Computers in Industry*, 123, 103327. doi: [10.1016/j.compind.2020.103327](https://doi.org/10.1016/j.compind.2020.103327)
12. Soori, M., Arezoo, B., & Dastres, R. (2023). [Artificial intelligence, machine learning and deep learning in advanced robotics: a review](#). *Cognitive Robotics*, 3, 54-70
13. Rahman, M. M., Shakeri, M., Tiong, S. K., Khatun, F., Amin, N., Pasupuleti, J., & Hasan, M. K. (2021). Prospective methodologies in hybrid renewable energy systems for energy prediction using artificial neural networks. *Sustainability*, 13(4), 2393. doi: [10.3390/su13042393](https://doi.org/10.3390/su13042393)
14. Shaqour, A., & Hagishima, A. (2022). Systematic Review on Deep Reinforcement Learning-Based Energy Management for Different Building Types. *Energies*, 15(22), 8663. doi: [10.3390/en15228663](https://doi.org/10.3390/en15228663)
15. Abbasnejad, B., Nepal, M. P., Ahankoob, A., Nasirian, A., & Drogemuller, R. (2020). Building Information Modelling (BIM) adoption and implementation enablers in AEC firms: a systematic literature review. *Architectural Engineering and Design Management*, 17(5–6), 411–433. doi: [10.1080/17452007.2020.1793721](https://doi.org/10.1080/17452007.2020.1793721)
16. Koskela, L., Howell, G., Ballard, G., & Tommelein, I. (2002). [The foundations of lean construction](#). In R. Best, G. De Valence, *Design and Construction: Building in Value* (chapter 14). Routledge
17. Bajjou, M. S., & Chafi, A. (2021). Exploring the critical waste factors affecting construction projects. *Engineering Construction & Architectural Management*, 29(6), 2268–2299. doi: [10.1108/ecam-12-2020-1097](https://doi.org/10.1108/ecam-12-2020-1097)
18. Toochukwu, A. C. (2025). Integrating Building Information Modelling (BIM) for effective construction planning, execution, and lifecycle management. *International Journal of Research Publication and Reviews*, 6(6), 4347–4364. doi: [10.55248/gengpi.6.0125.0621](https://doi.org/10.55248/gengpi.6.0125.0621)
19. Forcael, E., Martínez-Rocamora, A., Sepúlveda-Morales, J., García-Alvarado, R., Nope-Bernal, A., & Leighton, F. (2020). Behaviour and performance of BIM users in a collaborative work environment. *Applied Sciences*, 10(6), 2199. doi: [10.3390/app10062199](https://doi.org/10.3390/app10062199)
20. Berardi, U., & Jafarpur, P. (2019). Assessing the impact of climate change on building heating and cooling energy demand in Canada. *Renewable and Sustainable Energy Reviews*, 121, 109681. doi: [10.1016/j.rser.2019.109681](https://doi.org/10.1016/j.rser.2019.109681)
21. Ghansah, F. A. (2024). Digital twins for smart building at the facility management stage: a systematic review of enablers, applications and challenges. *Smart and Sustainable Built Environment*, 14(4), 1194–1229. doi: [10.1108/sasbe-10-2023-0298](https://doi.org/10.1108/sasbe-10-2023-0298)
22. Robinson, J. F., Foxon, T. J., & Taylor, P. G. (2015). Performance gap analysis case study of a non-domestic building. *Proceedings of the Institution of Civil Engineers - Engineering Sustainability*, 169(1), 31–38. doi: [10.1680/ensu.14.00055](https://doi.org/10.1680/ensu.14.00055)

23. Papadonikolaki, E., Krystallis, I., & Morgan, B. (2022). Digital Technologies in Built Environment Projects: A Review and Future Directions. *Project Management Journal*, 53(5), 501–519.
doi: [10.1177/87569728211070225](https://doi.org/10.1177/87569728211070225)