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Robotics and Sustainable Technologies in Construction: A Unified Perspective

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As the construction industry becomes increasingly aware of the environmental of building activities and material consumption throughout the project lifecycle, efforts to integrate sustainable practices have intensified. From remotely controlled drones surveying sites to large-scale 3D printers fabricating wall and slab modules, and robotic arms for precise assembly, the industry is cutting significantly on material waste and embodied energy. Yet, there are challenges to the adoption of these technologies, such as zoning regulations, insurance policies, and the continued need for codified professional expertise in programming and mechanics. Because the industry remains one of the world's largest emitters of greenhouse gases, the durability of low-carbon materials, smart design software, and modular optimization of energy consumption are just as much a product of smart design as disciplinary legislation. Inscribing such devices is only achievable with ongoing advocacy by policy makers, private organizations, and a continuous supply of expertise. Starting all projects with a circular metrics mindset is the strongest top-line revenue stream and most uniform climate plan in the same blueprints.

Keywords: Automation and Robotics, Sustainable Construction, Construction 4.0, Building Information Modeling (BIM), 3D Printing, Internet of Things (IoT), Material Efficiency.

Introduction

The urgency of climate change places building and construction at the center of global debates surrounding sustainability, as they have a significant impact on the environment (UNEP, 2025). Even with its significant environmental impact, the building and construction industry directly shapes how societies operate, live, and use energy. It is expected that the population residing in cities will grow to 2.5 billion by 2050 (UN, 2018), posing a challenge for rapid, sustainable development. This dual challenge must be addressed through non-traditional means. Robotics and automation, in conjunction with sustainable construction technologies, can serve as a template for future development that has a minimal impact on the natural environment. This proposed conjunction of two domain areas (sustainability achieved through robotics) can enable a development that will cater to the needs of the future. Implementation of robotics in the building and construction industry, then, is not only a productivity gain but also a cultural shift that aligns the sector with broader Sustainable Development Goals (SDGs), such as 1) SDG 9: Industry, Innovation, and Infrastructure, 2) SDG 11: Sustainable

Cities and Communities, 3) SDG 12: Responsible Consumption and Production, and SDG 13: Climate Action.

While the building sector propels global economic growth (BLS, 2025), buildings are also one of the most significant contributors to greenhouse gas emissions and raw material consumption throughout their lifecycle (Quale et al., 2012). Rapidly growing populations worldwide (USCB, 2025) and urbanization negatively impact the ecological environment (Liu et al., 2019). Industries such as the automotive industry have reaped the benefits of robotics for years, construction remained historically resistant due to the context-specific nature of the construction industry, which includes the fragmented nature of the industry and its stakeholders (BLS, 2025), site-specific changes that vary from project, heavy reliance on manual labor, and others. At the same time, over the last two decades, adoption patterns among stakeholders in the construction industry have changed, especially for technologies that facilitate robotics, including the increased adoption of digital technologies such as Building Information Modeling (BIM) (Fountain & Langar, 2018), drones (Albeaino & Gheisari, 2021), digital twins (Boje et al., 2020), and cloud collaboration platforms (Turk & Klinc, 2017). These technologies enable real-time data exchange, immersive visualization, and integrated decision-making, creating a foundation for robotics-driven automation. The adoption of these technologies can result in significant benefits, including improved safety (Webb and Langar, 2019), accuracy, and productivity (Sacks et al., 2018), while decreasing uncertainty and facilitating interdisciplinary teamwork. Increasing studies show that technologies supporting robotics, combined with green technologies, lead to a significant reduction in environmental impacts (Long et al., 2024).

Emerging robotics and automation technologies offer a credible avenue to address the dual stresses of rapid population growth and urbanization. Robotics can alleviate labor-intensive tasks such as precision bricklaying, painting, structural assembly, and site logistics tracking (Cai et al., 2018; Okonkwo et al., 2024). Studies show that robots improve productivity and safety while reducing errors and material wastage (Singh et al., 2021; Shehu & Abba, 2019). Furthermore, BIM, IoT sensors, and on-site 3D printing, combined with cloud-based collaboration (Turk & Klinc, 2017) and digital twin technologies (Boje et al., 2020), enable real-time monitoring and predictive analytics, driving operational and environmental efficiency. Sustainability as the prime driver in the initial planning and operation phases creates long-term economic and environmental return on investment. Robotics also enhances on-site safety, eliminates repetitive skilled labor shortages, and introduces consistency of quality. The simultaneous introduction of automation and energy-saving, resource-conserving technologies presents a strategic path for the construction industry, offering increased productivity without compromising environmental considerations or jeopardizing long-term sustainability.

Methodology

This study employs a systematic literature review to investigate the effects on the construction industry. It follows the Systematic Literature Review (SLR) approach to critically examine how automation and sustainability impact the construction industry. The examination is organized around five main dimensions that represent the most pressing concerns of modern-day construction: cost, safety, productivity, reduction of waste, and overall environmental performance. Each of these dimensions plays a basic role in determining not only the success of construction projects but also their alignment with sustainable development goals in the long run. By focusing on these five dimensions, this study aims to provide a well-rounded evaluation of both the economic and environmental impacts of technology adoption in the sector. Studies were included in multiple regions (Asia, Europe, North America, and the Middle East) to capture global adoption patterns and contextual differences. The selection covered a range of technologies robotics for bricklaying and painting, drones for site inspection, BIM integration, IoT sensors, and emerging tools such as digital twins and AI-based systems. Both large-scale infrastructure projects and smaller residential and commercial projects were represented to provide insights into scalability and applicability across different contexts.

This study conducted a Systematic Literature Review (SLR) in accordance with PRISMA guidelines to ensure transparency and reproducibility. Search was performed in Scopus, IEEE Xplore, and Web of Science using Boolean keywords related to construction robotics, automation, and sustainability, limited to peer-reviewed articles published between 2005 and 2025. From 250 initial records, 38 duplicates were removed, 167 were excluded after title and abstract screening, and 45 underwent full-text review based on inclusion and exclusion criteria. Ultimately, 21 studies were selected for their explicit link between automation/robotics and sustainability in construction, empirical evidence, and focus on the building sector. This structured approach provides a diverse evidence base across geography, technology types, and project scales, ensuring rigor and reproducibility in the review process.

Results & Discussion

Current literature expands on this review by classifying robotics' impact into five categories: labor, safety, cost, environment, and innovation. Cai et al. (2018) refer to robotics' ability to reduce reliance on hand bricklaying, while Singh et al. (2021) emphasize material savings using 3D printing. Delgado et al. (2019) instead, reports on obstacles to take up in the form of skill shortages and regulatory issues. Researchers also highlight the fact that it is not robotics alone that can bring sustainability, but it needs to be coupled with systemic technologies like BIM and lifecycle analysis. Zavadskas et al. (2017) argue that BIM allows decision-makers to anticipate carbon, cost, and time factors. Each of these studies shares one factor: robotics and automation can achieve their full sustainability only if it is implemented holistically at all stages of the project lifecycle.

A synthesis of the 21 studies indicates that benefits cluster around three dimensions: (1) Productivity and Cost Efficiency, (2) Safety and Risk Reduction, and (3) Environmental Sustainability. For example, Cai et al. (2018) and Singh et al. (2021) report significant reductions in material waste and labor costs through robotics and 3D printing, while Okonkwo et al. (2025) highlight safety improvements via autonomous painting robots. Conversely, barriers consistently fall into economic constraints, skill shortages, and regulatory hurdles (Delgado et al., 2019; Opoku et al., 2019). To move beyond a narrative review, we conducted a thematic analysis of the 21 selected studies using an inductive coding approach. Five major themes emerged: (1) Productivity & Cost Efficiency, (2) Safety & Risk Reduction, (3) Environmental Sustainability, (4) Technological Integration (BIM, IoT, AI), and (5) Adoption Barriers & Policy Drivers. Technology adoption patterns are illustrated in Table 1.

Table 1. Technological Adoption in Construction

Technology	**Author Names**
Self-Driving Construction Vehicles	Delgado et al. (2019)
Robotics and Automation	Cai et al. (2018); Delgado et al. (2019); Shehu & Abba (2019)
Building Information Modeling (BIM)	Fountain & Langar (2018); Sacks et al. (2018)
Drones for Site Inspection	Albeaino & Gheisari (2021)

Laser-based technologies	Brissi & Debs (2019)
Vision-based technologies	Elmousalami et al. (2025); Okonkwo et al. (2025)
Radio-based technologies	Singh et al. (2021)
AI and Reinforcement Learning	Elmousalami et al. (2025)
3D Point Cloud Reconstruction	Singh et al. (2021)

Table 1 provides a summary of commonly adopted technologies in construction automation and their associated references. These technologies play critical roles in processes such as real-time data processing, immersive visualization, precision handling, and surveying. Table 1 serves as the primary reference for understanding adoption patterns and their impact on productivity, efficiency, and safety in construction activities.

BIM Sustainability Adoption Drivers

Construction sustainability extends to material efficiency and involves systematic integration of environmental concerns in design, operation, and lifecycle management. Digital sustainability initiatives are increasingly supported by Building Information Modeling (BIM) and Lifecycle Assessment (LCA). Studies by Azhar (2011) and Chong et al. (2017) emphasize that BIM facilitates energy modeling, carbon footprint analysis, and resource optimization during early design stages. Similarly, Abanda & Byers (2016) highlight BIM's role in integrating LCA for evaluating environmental performance across the building lifecycle.

Adoption drivers identified in literature include cost savings, green certification requirements, and stakeholder pressure (Zavadskas et al., 2017; Chong et al., 2017). Efficiency and risk avoidance are also cited as critical motivators (Azhar, 2011). Collectively, these findings suggest that maximizing BIM's sustainability potential requires multi-stakeholder engagement and alignment with regulatory frameworks.

Green BIM, a plug-in with sustainability principles incorporated into BIM to facilitate energy modeling, estimation of water use, and daylighting simulations. In combination with lifecycle assessment (LCA), BIM allows decision-makers to contrast environmental impact from design to demolition. "*BIM and LCA methodologies enable practitioners to model and compare environmental performance before construction*" (Zavadskas et al., 2017).

Material Efficiency and Waste Reduction

Robotics and advanced manufacturing technologies such as 3D concrete printing (3DCP) significantly improve material efficiency and reduce waste, addressing one of the most pressing sustainability challenges in construction. Unlike traditional methods that involve cutting, trimming, or over-ordering, automated systems optimize resource use through precision application and on-demand production (Panda et al., 2018). Studies report that 3DCP can reduce material waste by up to 60% and improve resource utilization efficiency (Singh et al., 2021). Additionally, prefabrication and modular robotics further minimize waste by enabling controlled manufacturing environments and reducing site variability (Wu et al., 2020). These practices not only yield substantial cost savings but also advance circular economic principles by lowering raw material consumption and carbon emissions.

Economic and Policy Barriers

Economic and policy barriers remain a dominant theme across studies. Lowe (2015) and Opoku et al. (2019) emphasize persistent misconceptions about cost premiums for sustainable practices, while Oputu (2023) and Corona-Rios & Langar (2023) identify structural issues such as inadequate incentives, high training costs, and lack of standardization. Synthesizing these findings, barriers can be grouped into financial myths, institutional inertia, and technical complexity, all of which require targeted policy interventions and industry-wide education.

The synergistic advantage of green technologies and robotics is that they complement each other: robotics aims at productivity and safety, while digital sustainability software (BIM, IoT, AI) helps achieve environmental and lifecycle performance. Together, they enable Construction 4.0, which is described by Balasubramanian et al. (2024) as "technologies enabled by data, digital technologies, and automation that have gained momentum, promising unparalleled opportunities for maximizing sustainability goals."

Robotics, Automation, and Sustainability in Construction

The construction field is at a point where automation and sustainability are no longer distinct endeavors but are intertwined. Liu et al. (2024) point out that "*BIM, Human–Robot Collaboration (HRC), and Deep Reinforcement Learning (DRL) [are] the three pillars in the field*" of construction robotics. As they observe, the issue is not simply an issue of deploying robots but rather "*how does the adoption of robotics in the construction industry happen, why have robotics applications been few in actual construction site environments, and what is the long-term future of construction robotics.*" (Delgado et al., 2019, p. 100868)

From a sustainability point of view, González & Haddad (2023) believe that "*the integration of technological innovations, inclusive of the automation of processes in the built environment, is necessitated to enhance the levels of sustainability*."
They observe that studies combining automation and sustainability "*still require more research to leverage computational advances*". This demonstrates a fundamental gap between the potential of digital technologies and their actual utilization for sustainable facilities management.

Robotics technology is not limited to a purely technical approach but considers challenges relating to the circular economy. The review also suggests that robotics has direct contributions towards the sustainability trinity, economy, environment, and society through process efficiency in areas such as bricklaying, prefabrication, and material handling. They do, however, comment that the main reasons making the spread of robotic technology on construction sites impossible are high costs, low awareness, and a lack of suitably qualified labor.

Local studies provide more data on real-world gaps and opportunities. In the Kingdom of Bahrain, Nebrida & Gomba, (2023) determined that "*environmentally related management strategy is regularly practiced in approximately 75% of all projects completed, whilst overall sustainable construction practices, energy and material-based strategies, and waste-based strategies are occasionally applied in approximately 50%*". This shows that environmental awareness is relatively common, but without the regular application of sustainable construction technologies.

This synergy between automation and sustainability receives further boost in more recent literature, particularly in the case of Automated Sustainable Construction Engineering Management (ASCEM), which (Elmousalami et al., 2025) described as "*an AI-based system of automated applications aimed at optimizing construction processes with emphasis on sustainability, efficiency, and environmental* *footprint*." The ASCEM model integrates technologies such as digital twins, IoT, and green AI to enable real-time monitoring, predictive analysis, and carbon footprint analytics." As the authors note, "*AI applications in construction engineering and management promote sustainable construction by reducing environmental footprint and enhancing energy efficiency*." Similarly, Shehu & Abba, (2019) emphasize that building automation results in "more energy efficiency, reduced operating and maintenance costs, improved indoor air quality, and enhanced occupant comfort and productivity." These benefits are no longer theoretical; they are increasingly being realized through intelligent robots, autonomous heating, ventilation, and air conditioning systems, and sensor-based structural health monitoring. The problem, however, lies in its implementation. "*Fragmented workflows, legacy systems, and lack of expertise*" still plague the industry-wide adoption of these technologies (Elmousalami et al., 2025). The future of construction, then, demands not merely technical innovation but systemic change, wherein automation is not an accessory but a fundamental approach to sustainable development. Cumulatively, these studies present an urgent research challenge: In what ways can automation and robotics drive efficiency as well as place sustainability at the heart of construction practice? Construction robotics is "not only about technical performance but also about aligning with sustainability and the circular economy". Linking these dimensions is vital if the sector is to move beyond discrete solutions to an integrated model in which technological innovation and environmental responsibility reinforce one another.

Integrating Lean Thinking, Automation, and Modularization to Minimize Waste and Transform the AEC Industry

Figure 1 synthesizes insights from the literature reviewed in this study, illustrating how research themes and practical issues differ between Lean, Automation, and Modularization (LAM) concepts and their industry adoption. Figure 1 highlights that while academic research emphasizes LAM integration, industry adoption remains constrained by economic and technical barriers.

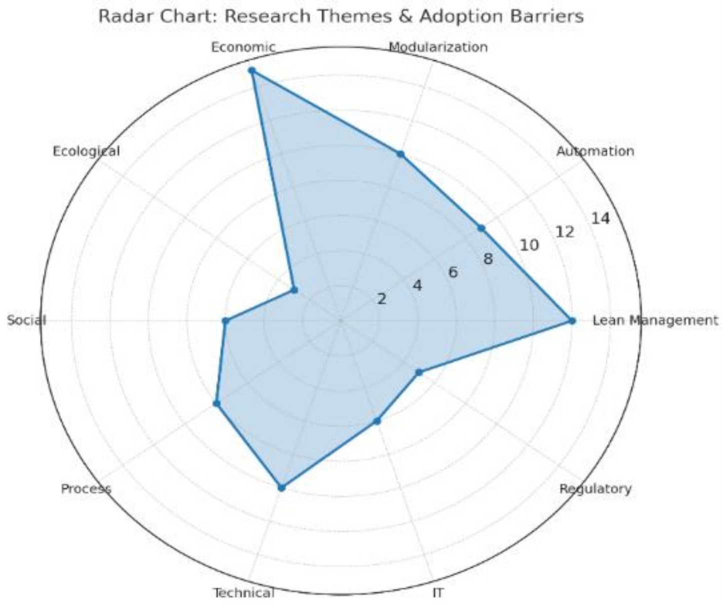

Figure 1: Research Themes and Adoption Barriers

This research demonstrates that robotics and sustainability are not parallel paths but complementary. Construction 4.0 is the umbrella under which these synergies are unleashed. Barriers include institutional inertia, myths of cost premiums, and skilled labor shortages, but these can be overcome by focused policy, education, and industry coordination. Looking ahead, the next wave of research must address real-world deployment of integrated systems, for instance, digital twins combined with robotics for predictive performance management. Policymakers must provide incentives, while academia and industry must collaborate to close skills gaps. The future of construction rests on its ability to grasp automation as a means for sustainability, so that the built environment is productive and resilient in the face of global climate change.

Robotics–Sustainability Integration Framework (RSIF)

Based on the thematic synthesis of 21 studies, we propose the Robotics–Sustainability Integration Framework (RSIF) as a structured model for aligning automation technologies with sustainability objectives in construction. The framework consists of three layers:
(1) Enabling Technologies (Robotics, BIM, IoT, AI),
(2) Sustainability Drivers (Material Efficiency, Energy Optimization, Waste Reduction), and
(3) Outcome Dimensions (Productivity, Safety, Environmental Performance).
This framework contributes a novel perspective by synthesizing fragmented findings into a structured model that can guide both research and practice.

Conclusions

This study moves beyond a narrative synthesis by introducing the Robotics–Sustainability Integration Framework (RSIF), which conceptualizes how enabling technologies interact with sustainability drivers to deliver productivity, safety, and environmental benefits. Robotics offers answers to some of the industry's most significant pain points: drastic labor shortages, the need for accuracy in complicated tasks, and the reduction of workplace risks. Meanwhile, sustainable technologies like 3D printing, the Internet of Things (IoT), and Building Information Modeling (BIM) bring long-term efficiency, material economy, and environmental accountability. Combined, these technological advancements not only solve short-term issues but also bring construction practices in line with global sustainability objectives, making the industry a positive contributor to both productivity and the environment.

Despite this widespread advancement, stringent obstacles continue to block widespread adoption. Institutional resistance, misconceptions about financial implications, and narrow incentive structures still hamper the transformation of the industry. Lowe (2015) highlighted this persistent issue, noting that "Developers have the mistaken assumption that capital costs will rise when they adopt environmentally sustainable practices," a perception that dissuades stakeholders from pursuing green options. Likewise, Opoku et al. (2019)) reiterated that "The lack of guidelines and incentives for sustainable construction tends to discourage companies from embracing fully these practices," highlighting how the lack of organized policies and rewards creates a barrier to industry-wide adoption. These misunderstandings and loopholes entrench caution, retarding innovation that could otherwise be routine practice in the industry.

A further element of resistance is cultural inertia, the embedded routines, long-standing habits, and traditional practices that retard progress. Construction firms are prone to prefer tried-and-tested methods to risking more novel, technology-based approaches. However, the role of education and awareness has been the most potent force for removing this obstacle. Nguyen et al. (2019) depicted this by stating that "Education had the strongest relationship with sustainability," showing how awareness campaigns, skills training, and academic curricula foster an attitude of responsibility and openness towards sustainable practices. By developing knowledge and infusing sustainability into professional culture, the industry can erase old habits and accelerate the adoption of robotics and automation.

Synthesizing across studies, robotics and automation consistently demonstrate dual benefits: economic viability and environmental responsibility. Empirical evidence from Singh et al. (2021) and Cai et al. (2018) confirms cost reductions and material efficiency, while Shehu & Abba (2019) and Elmousalami et al. (2025) highlight energy savings and improved indoor air quality. These findings collectively challenge the misconception that sustainability entails higher costs, reinforcing that technological adoption can align profitability with global sustainability goals. By minimizing both labor reliance and resource wastage, robotics directly tackles two of the greatest cost drivers in construction. Such results demonstrate that cutting-edge technologies can be aligned with the financial drivers of the industry while supporting global sustainability goals. Taking this momentum a step further (Balasubramanian et al., 2024) reaffirmed this point of inflection by clarifying that "Construction 4.0 technologies enabled by data, digital technologies, and automation have gained traction," indicating that digitalization has emerged as a force to drive changes in the industry at a systemic level. Lastly, for the construction industry to fully utilize these opportunities, sustainability needs to be repositioned not as an added cost but as both an environmental responsibility and an economic benefit. Rather than viewing it as a burden, stakeholders need to adopt sustainability as a source of innovation, resilience, and long-term profitability. Bamgbade et al. (2017) summed up this spirit by concluding that "Sustainability addresses the creation of a favorable built environment that meets humans' present needs without jeopardizing the ability of the future generation to meet theirs," strengthening the moral and practical basis of sustainable development. This assertion sums up the true vision of incorporating robotics and green technologies, constructing tomorrow responsibly today. With the combined efforts of technology, education, and sustainability, the construction industry can evolve into an industry that not only constructs efficiently but also protects the future.

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