Robotics and Automation in Precast Modular Housing: A Review of Technologies, Integration, and Challenges

Durga Parvateesh Siligisetti[1*], Shreekanth Birgonda[2], Ajay Kumar[3]

[1*] Student, Department of Civil Engineering, National Institute of Technology, Delhi, India
[2] Research Associate, Department of Civil Engineering, National Institute of Technology, Delhi, India
[3] Associate Professor, Department of Civil Engineering, National Institute of Technology, Delhi, India
*Email ID: durgaparvateesh@gmail.com

Abstract

Precast modular housing has progressed from early mechanised formwork, basic conveyor systems, and manual quality inspection to advanced robotic manufacturing environments. Initial practices relied on semi-automated casting and simple material handling. In contrast, modern construction increasingly adopts fully robotic cells capable of reinforcement placement, concrete casting, surface finishing, and inspection of precast panels and volumetric housing modules. This shift reflects enhanced human–robot collaboration, with workers supervising automated systems and coordinating module handling and installation. The advanced technologies like Building Information Modelling (BIM) and digital twin technologies enable seamless data flow from design through fabrication and assembly. At the same time, quality assurance is strengthened through laser scanning, embedded sensors, and machine-vision-based automated rebar tying and dimensional verification. This review synthesises recent research and industry practices on robotics and automation in precast modular housing, covering both large-scale factory production and small-scale construction applications such as plastering, painting, and tiling. It examines BIM-driven robotic workflows, automated quality-control methods, and flexible robotic configurations that support the mass customisation of layouts, facades, and structural systems without compromising productivity. Despite clear benefits in accuracy, safety, material efficiency, and project delivery speed, challenges remain, including high capital investment, limited interoperability between BIM and robotic control systems, a lack of standardised codes for automated construction, and the need for workforce training and organisational change. The paper highlights emerging solutions such as reconfigurable robotic cells, AI-optimised concrete production and curing, real-time sensor-based quality monitoring, and updated structural standards, positioning robotics as a key enabler for scalable, high-quality precast modular housing in modern construction.

Keywords: Precast Modular Housing, Robotics, BIM, IoT, Automation, Construction

1 Introduction

1.1 Automation in Construction Industry – Background and Need

Precast modular housing is one of the highest levels of industrialisation in the construction industry, with structural components and volume-sized modules manufactured in a factory-located, closed environment before being assembled on site. This manner of production, by default, promotes standardised production lots, repetitive production, and quality assurance. However, the methods of production are still primarily based on equipment-based systems and systems that rely on human workers, with some labour required, rather than fully automated robotic systems.
The research being conducted in Construction 4.0 highlights the role that robotics plays in linking digital design to physical production[1]. The use of robotics to connect the digital design and physical production processes in the precast modular housing sector is significant because it creates an efficient, standardised way to manufacture wall panels, slabs, and volumetric units that enable programmable automation. Earlier research on robotics in the construction industry has shown that the robotization level in factory-controlled environments is significantly higher than on non-structured

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construction sites[2]. In precast modular systems, dimensional deviations and reinforcement misalignments can propagate throughout the module stack due to connection errors, resulting in a combination of structural and finish issues caused by module modulation during installation. The use of robotics provides a higher standard of geometric accuracy and digital traceability, which are essential for maintaining modular integrity. Therefore, automation in precast modular housing should be viewed as an improvement towards manufacturing-grade production systems integrated by digital continuity, process optimization, and real-time quality monitoring.

1.2 Productivity, Safety, and Labor Challenges in Conventional Construction

Conventional construction continues to assign excessive amounts of human effort and site-specific criteria to complete many tasks that require human effort, such as placing rebar, assembling forms, and visually inspecting built structures. The fragmented nature of these tasks often results in reduced productivity, variability in dimensions, and excessive consumption of material due to a lack of certainty[3], [4]. Modular housings produced using robotics-enabled systems are constructed in controlled factory settings, thereby benefiting from automation and improving precision and accuracy through the repeated fabrication of identical products. High detection rates and decreased production time have been demonstrated by vision-guided robotics being used to tie rebar while fabricating slabs[5] and millimetre-level tolerancing verification using automated terrestrial laser scanners will reduce or eliminate rework as well as the need for manual inspections[6], [7].

In addition to increasing productivity, traditional construction methods have also generated increased material waste and embodied carbon due to rework, overdesign, and poor resource management. Robotic fabrication of precast construction and additive manufacturing enable optimizing material placement during precast component construction, thereby reducing the use of materials such as concrete and corresponding reductions in CO_2 emissions[8], [9]. Standardized modular production increases the ability to trace the history of a component and improve upon its chances for being disassembled and reused in the long term, therefore contributing towards the goal of creating a circular economy and sustainable lifecycle processes in construction[10]. Therefore, the use of robotics in precast modular housing to increase productivity and safety serves the same goal as optimism in construction, complementing the industry's larger goals.

1.3 Objectives and Scope of the Review

The study on robotics and automation gives a thorough assessment of current trends and advancements in robotic automation and robotics related to prefabricated modular housing systems. It encompasses technologies such as robotic fabrication, digital inspection systems, BIM-integrated manufacturing workflows, and human-robot collaboration models, and their impact on sustainability compared to conventional construction. Research on Construction 4.0 explores how digital optimization influences the overall growth of the construction industry[1]. This focus is only on the automation portion, where robotics can be applied at scale.

This literature review focuses on the principal areas of prefabricated modular housing production: Reinforcement automation[5], Automated dimensional verification[6], [7], BIM-driven robotic fabrication[8], [11], Additive manufacturing systems[9], Prefabricated components of buildings and fully fabricated buildings. The literature review aims to provide an in-depth analysis of technological advancement and integration obstacles, as well as a future pathway to achieving high levels of modular housing production.

2 The Evolution of Robotics and Automation in Construction

The development of automated systems for precast modular housing production has shifted from simple process optimization tools to the incorporation of advanced systems capable of performing automated construction functions using robotic equipment. The earlier research has focused on modelling the production of modular housing in controlled factory environments and looked at different flows of materials through a factory production line, as well as how all the different manufacturing processes work together within the controlled environment of the factory[12]. Modelling these processes enabled the development of the conceptual framework to facilitate the industrialisation of housing production. Later advancements focused on developing digital systems to inspect and verify precast components during assembly. The implementation of terrestrial laser scanning enabled automated comparison of as-built precast components with their corresponding elements in the BIM model, allowing identification of discrepancies before assembly[6], [13]. Also, advances in clustering and classification algorithms enabled automated identification of embedded reinforcement and connection sleeves, thereby reducing the risk of assembly failure due to manufacturing tolerances[7]. Automation in precast housing production has advanced to the use of direct robotic systems for manufacturing precast products. Robotic concrete spraying systems have enabled the automated production of ribbed precast components with varying thicknesses, thereby reducing the need for complex formwork and enabling greater geometric flexibility in precast building materials[9]. Automation related to the placement of reinforcing steel has also advanced to include vision-guided systems for robotic tying of steel elements. By integrating perception and manipulation, vision-guided robotic systems represent the evolution from inspection-based automation to active robotic production[5]. The development of a design-to-manufacture framework that leverages BIM has improved integration between digital design models and robotic building systems by converting BIM-derived geometry into programmable commands for robotics. These improvements are creating a closer relationship between design intent and the actual construction process[8], [11]. Together, these changes represent a transition away from stand-alone automation technologies toward digitally integrated robotic systems in modular housing manufacturing environments.

Prefabricated modular housing has many similarities to manufacturing systems, such as the use of standard parts, centralised production settings, and repetitive production processes performed across different phases of production (design, fabrication, finishing, and delivery). Therefore, due to these similarities, prefabricated construction has increasingly adopted manufacturing-derived automation strategies, and robotic manufacturing is often considered the top automation level for the structural prefabrication process[14]. However, modular housing manufacturing differs from traditional manufacturing due to the vast number of variable designs, the stringent structural tolerances that must be adhered to, and the logistical limitations of transporting a finished module to a construction site. These issues drastically restrict the potential for rigid production lines and increase the need for robotic systems that can adapt to architectural and structural changes. Thus, BIM-based computational frameworks, incorporating CAD-CAM methodologies, have been proposed to achieve digital continuity from the design model to the robotics production system[8]. Despite these advancements, Automation in modular housing is limited to single modular production processes, such as robotic rebar tying[5], automated geometric verification [6], point cloud-assisted connection inspection[7] and simulated coordinated robotic assembly[15]. However, studies focused on Construction 4.0 show that robotic adoption is growing; however, there has only been limited success in fully integrating robotics across the entire modular production process due to two primary challenges: interoperability and the lack of consistent investment in the residential construction sector[1]. Nevertheless, because modular housing is amenable to high levels of predictability and repeatability, the modular housing sector presents logical opportunities for the large-scale deployment of future robotic construction systems.

Table 1. Comparative overview of reviewed studies on robotics and automation technologies applied to precast modular housing.

Reference	Focus Area	Technology	Contribution to Precast Modular Housing
[1]	Construction 4.0	AI, IoT, autonomous systems	Framework for intelligent and autonomous construction
[2]	Bibliometric analysis	Scientometric mapping	Evolution of robotics research in construction
[4]	Robotic systems classification	In-situ robotic technologies	Systematic categorization of construction robots
[5]	Robotic rebar tying	Vision-guided robotic arm	Automated reinforcement placement in precast slabs
[6]	Quality assessment	Terrestrial laser scanning	Millimeter-level tolerance detection in precast elements
[7]	Connection verification	AI-based point cloud recognition	Automated sleeve and reinforcement detection
[8]	BIM-driven fabrication	BIM–robot interface	Digital-to-robot fabrication pipeline
[9]	Robotic concrete spraying	Additive manufacturing	Material-efficient precast element fabrication
[10]	Robotic refabrication	Robotic manipulation systems	Modular disassembly and circular reuse potential
[11]	Computational BIM–robot workflow	Parametric robotic control	CAD–CAM integration for modular fabrication
[12]	Modular production modeling	Simulation & process modeling	Optimization of modular production workflows
[14]	Prefabrication automation review	Industrial automation systems	Assessment of automation maturity in prefab construction
[15]	Robotic coordination	Multi-robot systems	Integrated robotic assembly in prefabrication
[16]	Human–robot collaboration	Collaborative robotics	Safer human–robot interaction in prefab factories
[17]	Digital twin systems	Cyber-physical integration	Real-time monitoring of modular production

3 Types of Robots and Automated Systems in Precast Modular Housing

The use of robotics has been a pivotal component of increasing productivity and accuracy in the prefabricated modular homes production process. Robotic systems in factory-based modular construction typically operate within four functional categories: fixed industrial robotic manipulators; mobile robotic platforms; fabrication robots; and inspection robots with various sensing technologies. Fixed industrial robotic manipulators form the backbone of automation in precast factories and perform repetitive, accuracy-critical tasks during precast production, including the placement of form reinforcement, welding, material handling, and surface finishing within structured manufacturing cells. Precast processes occur in a controlled precast factory environment, with a clearly defined workflow. Robotic manufacturing is the most advanced level of automation used in structural prefabrication[14]. The research on integrating robotic manipulators into digital design environments is detailed. The ability to translate design geometry into robotic motion trajectories through BIM-based computational pipelines enables automated manufacturing without extensive manual reprogramming[8], [11]. This seamless transition from digital to physical, i.e., a direct correlation between physical and virtual geometry, maintains geometrical accuracy across production runs. Additionally, the industrialization of prefabricated modular housing manufacturing will continue to involve new robotic assembly lines that facilitate the mass customization of housing through automated manufacturing processes[3]. Figure 1 illustrates that robotic industrialization enables mass-customized housing production through automated assembly-line integration.

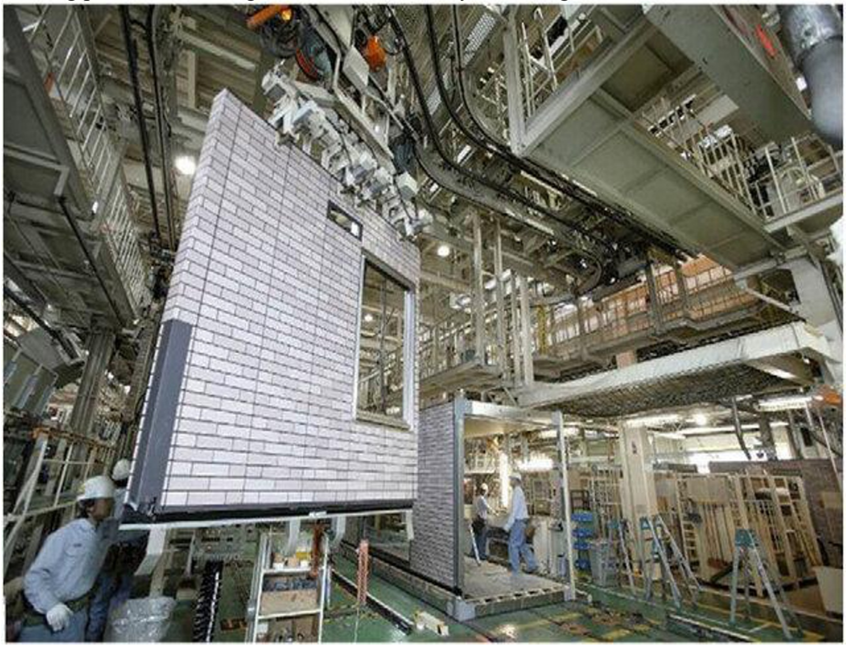

Fig. 1. Sekisui Heim uses robotic industrialization to enable efficient personalization of buildings during assembly-line manufacturing. (Image: courtesy of Sekisui Heim)[3]

While many fabrication tasks are performed using stationary manufacturing robots in fixed robotic cells, the need for mobile robots to transport and position large modular prefabricated components is also increasing to enable these activities. Mobile platforms are utilized to transport large precast wall panels and to enable accurate alignment of volumetric modules before assembly. Robotic coordination systems can be used with assembly logic embedded in digital building elements, allowing robots to use this information to determine when and how to position the different modules relative to each other, enabling the assembly process to proceed as planned[15]. Robotics also continues to improve current methods of reinforcing steel (rebar) fabrication and rebar inspection during construction. Robotics equipped with vision guidance technology to tie rebar can use RGB-D technology combined with image processing and path planning techniques to recognize rebar intersections, and then perform rebar tying operations automatically with a high degree of accuracy, resulting in a decrease in labor-intensive work and a considerable improvement in the consistency of the way rebar is placed[5]. Additive manufacturing technologies (e.g., automated robotic concrete sprayers) have enabled the programming of ribbed structural component deposition with varying thicknesses, without the need for complex formwork, thereby increasing geometric flexibility[9]. Quality assurance inspection systems have also improved by incorporating sensors into the quality assurance process. For example, laser scanning technology enables dimensional confirmation by comparing the point cloud to BIM-based models. Automated algorithms identify embedded objects, e.g., reinforcing bars and sleeves, which helps to ensure accurate alignment of plastering and assembly[6], [7]. Current research is exploring how to incorporate inspection data into digital twin environments for real-time product monitoring and traceability, thereby enhancing audit connections between fabrication and quality assurance[17]. Figure 2 represents the types of robotic systems used in precast modular housing production.

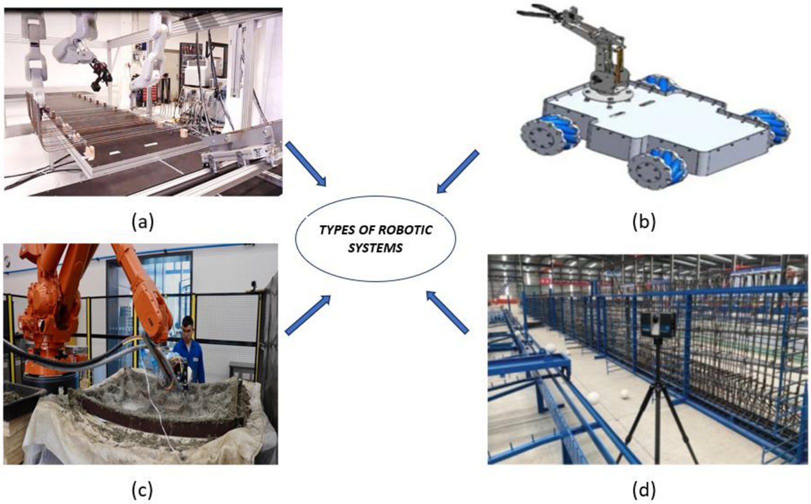

Fig. 2. The robotic systems used in precast modular housing production: (a) reinforcement automation[18], (b) robotic material handling[19], (c) additive fabrication[9], and (d) automated inspection[20].

4 Automation Technologies and Enabling Tools

The production of prefabricated modular homes through automated systems is based on an integrated set of technologies that combine robotic hardware, digital (CAD) design models, sensing devices, artificial intelligence, and continuous, real-time data exchange in a manufacturing environment. Building Information Modeling (BIM) serves as the foundation for data related to the modular construction process. Still, there remains a significant gap in converting BIM-generated geometries and semantic information into commands executable by robotics. Recent advancements in design-to-manufacturing systems illustrate how BIM-generated geometries can be decomposed into compatible fabrication logics that robots can utilize to execute robotic trajectories on parametric modular component models through scripting tools and APIs specific to robots[8]. Additional advancements in BIM-based robotic manufacturing frameworks will allow digitally generated models to create automated sequences of activities (task sequences), control the automated transport devices that move to the next workpiece along the assembly line, and write the assembly instructions for the construction of the modular home with minimal manual programming[11]. The automated processes of working with the BIM-robot interface relative to the production of modular homes would include: robotic interpretation of reinforcement layout drawings; robotic generation of the welding and tying paths; control of trajectories in additive manufacturing; and verification of the alignment of modules, with the goal of reducing human error and increasing the scalability of producing modular homes in repetitive operations. Adaptive robotic operation in modular home manufacturing facilities also depends on both perception technology and intelligent decision systems. Sensor and feedback mechanisms, particularly terrestrial laser scanning, provide sensor-based feedback to compare fabricated geometry to Building Information Modeling (BIM). This enables automatic deviation analysis at millimeter accuracy[6] and supports advanced point cloud-automated processing to recognize integrated rebar and connection sleeves embedded within precast components, resulting in shorter inspection time and greater reliability of connections[7]. The transfer of inspection results into digital twin environments creates a continuously synchronized communication link between physical production and virtual models, producing traceable quality records for each modular unit[17]. Figure 3 illustrates the fundamental interdependency between material, structure, and production in automated precast systems. The optimisation of precast elements requires simultaneous consideration of material efficiency, structural design, and automation level.

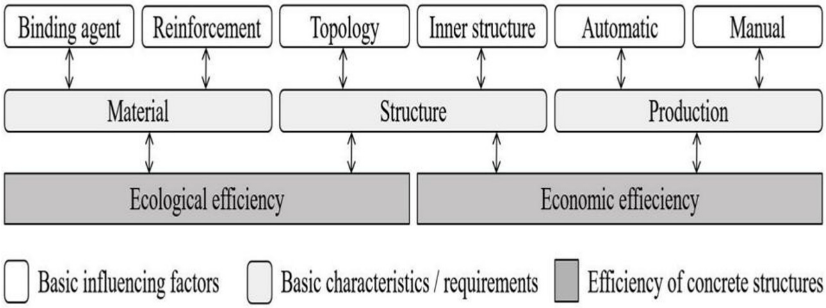

Fig. 3. Classification of the key interdependencies in precast concrete production[21]

AI also enhances the adaptive capability of robots by enabling perception-based fabrication tasks, such as reinforcement tying via machine vision, allowing algorithms to identify rebar intersections and assist robotic manipulators with automatic tying operations[5]. AI-based systems can also use production data analysis to optimize production scheduling, predict and prevent equipment failure, and improve resource allocation within modular manufacturing facilities. Construction 4.0 research continues to expand on how the Internet of Things (IoT) and computer-mediated collaboration will continue to augment real-time monitoring capabilities, sensor-based decision-making, and integrated data flows across the construction system[1], as control systems operate within a unified ecosystem and across multiple phases of production. Together, these technologies support the transition from conventional modular production toward fully monitored cyber-physical manufacturing environments in which robotics, digital models, and intelligent control systems operate within a unified ecosystem.

5 Robotic Applications in Construction Operations

Robots are becoming popular tools for building the components that form precast modular homes (i.e., precast panels and stacks). Most precast modular home production process takes place in the factory; therefore, robotics equipment provides significant benefits to the process; such as handling materials, manufacturing concrete products, assembling prefabricated products, inspecting them, and managing their lifecycle. One of the most significant logistics tasks in precast modular housing production is moving large precast concrete wall panels or volume modules from one manufacturing station to another. These tasks typically require the use of cranes or crane-like devices to complete them. Using robotic or semi-automated handling devices increases safety during manual lifting and improves the precision with which panels or modules are aligned to their specified locations. The research in the Construction 4.0 area highlights

how integrating IoT-based technologies (e.g., sensors) and robotics can be beneficial in optimizing the internal logistical movement of products (i.e., pre-manufactured parts) within the factory where they are manufactured, as well as reducing logistical bottlenecks throughout the manufacturing and assembling processes[1]. In addition, through utilizing an automated component-based mapping framework, automated assembly of robotic equipment can be accomplished by embedding assembly logic (computer code) into building information modeling (BIM) systems. These systems provide instructions to robotic equipment on how to perform stacking and align the recently assembled components or products accurately according to predetermined, digitally represented specifications[15]. The use of robotic excavation does not play as large a role as it does in traditional construction; however, improving internal logistical support within precast modular manufacturing facilities by utilizing robotic or semi-automated equipment has enhanced overall productivity and safety.
Concrete fabrication, prefabrication assembly, and quality control processes benefit greatly from robotic technologies. Automated concrete spraying systems with programmable deposition of ribbed structural elements, using trajectory-planning algorithms, which minimize the requirement for complex formwork and facilitate the optimization of structural geometries using additive manufacturing methods[9]. Robotic manipulators can also aid concrete placement and compaction in conventional precast casting operations, while fabrication workflows based on BIM ensure that deposition paths are congruent with the digital design model[11]. Automation also improves the efficiency of prefabrication through the use of robotic reinforcement preparation along with vision-guided rebar tying systems, thus supporting consistency and productivity for repetitive fabrication tasks[5]. In modular housing production, robotics is widely used for inspection and quality control. Terrestrial laser scanning is used to automate dimensional verification by comparing point cloud data obtained from scanning with BIM models of the processed modules[22]. Automated dimensional inspection of precast panels has been successfully demonstrated, with data acquisition, edge extraction, and automated dimensional verification integrated into a continuous workflow using terrestrial laser scanning, as shown in Figure 4.

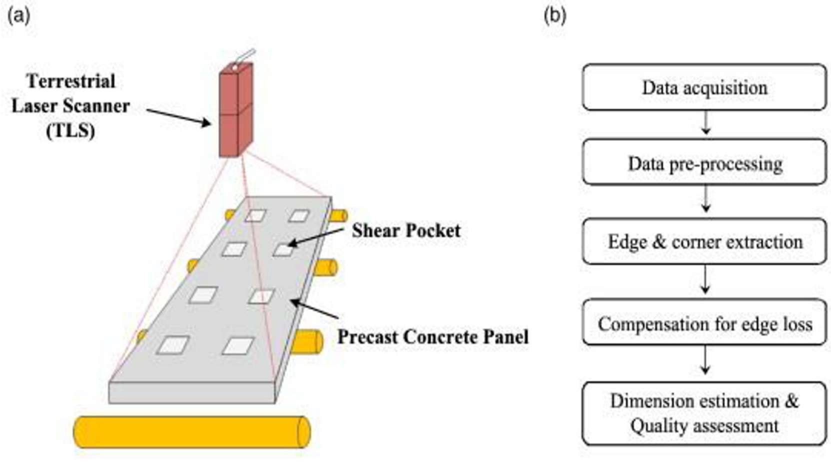

Fig. 4. The proposed technique for assessing dimensional accuracy in precast concrete. (a) Illustration of the complete system configuration. (b) Steps involved in the dimensional quality assessment process[22].

Advanced algorithms can also assist in identifying embedded reinforcements and connection sleeves to verify accurate alignment during assembly[7]. The integration of inspection data into digital twin environments enhances the traceability of inspections and supports real-time monitoring throughout the entire lifecycle of precast structures[17]. Emerging robotic refabrication systems also enable modular structures to be disassembled and reconfigured based on updated digital models, supporting circular construction strategies and extending the lifespan of modular housing components[10].

6 Human Robot Interaction and Safety

Robots play a substantial role in the production of modular precast concrete construction. They are mostly used on factory-controlled production lines, not on fully automated job sites. For this reason, the development of automated systems for modular construction has focused on creating collaborative human-robot work environments rather than fully replacing human workers. Robotic systems and human-skilled labor collaborate in work settings to increase the scalability, efficiency, and safety of manufacturing processes. Collaborative robotic cells integrate computerized design technologies, human supervision, and industrial robot manipulators to achieve efficient manufacturing. Research on the automation of structural prefabrication has indicated that robots achieve their highest productivity when integrated into coordinated production systems rather than used as independent workstations[14].
Studies have also shown that human-robot collaboration allows for greater flexibility in handling complex fabrication tasks by leveraging the precision of robotics with human oversight and design decision-making[16]. In modular manufacturing facilities, robots are used most frequently for the performance of repetitively performed and precision-dependent activities such as placing reinforcement, finishing surfaces and handling concrete, whereas human operators control the production sequence, quality assurance, and exceptions. The use of building information modeling (BIM)-based robotic fabrication systems to develop collaborative workplace environments enables the development of digital representations of fabricated components and their associated robotic operations allowing human operators to visualize and plan the paths of robotic operations and assembly sequences prior to physical execution of those activities[11]. Figure 5 shows the human–robot interaction framework for precast modular housing production, illustrating the transition from manual tasks to robotic systems and collaborative supervision environments.

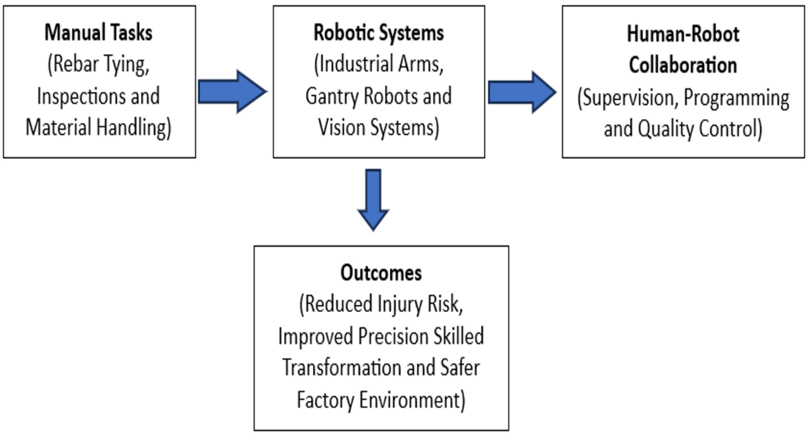

Fig. 5. Human–robot interaction framework in precast modular housing production

The incorporation of assembly logic into the digital representation of components in a component-oriented robotic coordination system enables the execution of work by robots according to predetermined states of components, with the presence of only human intervention when there is a deviation from what is expected[15]. Consequently, the collaborative robotic cells operate as semi-autonomous manufacturing systems under human supervision and are used to optimise the system performance. The safety of all workers and the transformation of the workforce are critical to the ongoing adoption of robotics in modular housing manufacturing. The use of robots to automate the assembly process reduces exposure to dangerous and physical tasks, such as repetitive tying of reinforcement and heavy lifting[5]. In a similar capacity, technologies that facilitate automated inspection reduce the need to manually measure components located near large precast members, as dimensional accuracy can be verified using laser scanning and digital analysis from a safe distance[22]. However, at the same time, due to the availability of collaborative robotic environments, new system-based safety protocols will need to be developed to address interactions between humans and robots. This need for development of new regulatory frameworks and operating guidelines for autonomous and semi-autonomous systems is demonstrated by the Construction 4.0 research[1]. Current safety mechanisms within modular manufacturing include sensor-based collision detection, monitoring of safe distances between workers and robots, identifying designated work zones for robots and providing emergency stop systems.

By utilizing digital twin technology, risk management regarding the usage of robotic systems can be optimized by providing the ability to simulate robotic jobs prior to performing them physically, and providing designers with opportunities to identify and mitigate any potential risks that could occur during the design process[17]. With increased use of robotic systems within housing modules, the role of the human workforce in the production of modular housing will also be transformed. Automation does not replace workers; however, it changes the duties they perform by enabling digital monitoring, the management of robotic system development and the development of data-driven decisions. Workers who are involved with fabrication systems that use BIM technology will require the use of parametric modelling and controlling robotic devices[8], [11], while inspections performed using point clouds will require skills both in digital modelling and analysis of data[7].

7 Project Management and Economic Implications

Robotics impacts project management and economic planning in the precast modular housing market through the establishment of production-line configurations, capital investment decisions, and long-term operational efficiency. Unlike traditional construction projects, the production of modular houses follows a manufacturing process logic in which robotics is integrated into the factory system rather than being used as a temporary project construction tool. Therefore, the productivity of modular factories can be represented as a function of cycle time, defect rate, labor intensity, and workflow synchronization. By reducing the variability of tasks performed and decreasing the quantity of rework associated with individual tasks, robotic automation will positively impact these elements of modular factory productivity. Vision-guided reinforcement tying devices reduce the overall time spent on manual labour associated with tying reinforcing bars as well as significantly improve the ability to detect intersections between reinforcing bars accurately; this results in increased production cycle times and line balance of slabs[5]. Automated dimensional inspection devices improve the productivity of modular factories by detecting deviations from specified dimensions early on in the dimensional inspection process, thereby preventing cumulative tolerance discrepancies throughout all stages of module stacking; thus reducing costly reworks due to subsequent deviations or errors[13]. Similarly, the use of computer-generated point-cloud data to verify alignment of connections improves the reliability of connection assemblies and reduces connection assembly time[7]. Although using robotics will increase the level of fixed capital investment associated with modular housing construction, studies on Construction 4.0 have shown that one of

the largest obstacles in adopting automated processes remains their initial high cost[1]. Nevertheless, the repetitiveness of the production of precast modular housing provides an opportunity to spread out fixed capital expenditures over a large volume of production, thereby increasing the project's long-term economic viability.
A lifecycle benefit is the opportunity to simulate the fabrication cycles of the project before actual fabrication by using Building Information Modeling (BIM) to create a design-to-manufacture pipeline, which will optimize the sequenced applications of robotic technology and the cycle times for robotics[8], [11]. Internet of Things (IoT)-enabled monitoring solutions can improve the dependability of robotic systems for scheduling reasons by tracking machine performance in real time and workflow progress[1]. The financial viability of robotics ultimately depends on scalability, as technologies such as automated concrete spraying become economically feasible when large volumes of standardized components are produced[9]. Furthermore, the potential lifecycle benefits of using robotics to reform modular structures for reuse will result in a lower waste of materials and increased life expectancy for components[10]. Additionally, digital twin technologies will be leveraged to increase the long-term ROI through predictive maintenance and equipment in operation monitoring[17].

8 Sustainability and Environment Benefits

Robotics has played an important role in sustainable precast modular homes through improvements related to industrialized production and materials optimization. Automation using terrestrial laser scanning provides millimetre accuracy by verifying dimensional accuracy prior to assembly, leading to reduced fabrication errors, rework, and material waste during production. Furthermore, advanced point-cloud identification technology allows for accurate verification of reinforcement and sleeves, improving structural alignment and reducing waste of materials[7]. Through vision-guided robotic tying of reinforcement, robotics aids in creating consistent connections, thus reducing rework due to defects in the structure[5]. Several new technologies, such as additive robotic construction or automated concrete spraying, enhance resource efficiency by creating optimized ribbed or thin-shell geometries with controlled thicknesses, leading to less concrete being used and therefore lowering the associated embodied carbon[9]. In addition to efficient production, robotics also provides an opportunity for circular modular construction through processes that allow components to be disassembled and reassembled for reuse[10]. The use of digital twin technology enables each modular unit to have a continuously traceable lifecycle, which supports condition-based maintenance and enhanced reuse decision-making[17].

9 Challenges and Barriers to Adoption

Despite significant technological advances in robotic reinforcement, inspection, and digital fabrication, several technical, economic, regulatory, and organizational barriers continue to hinder the widespread adoption of fully automated precast modular housing solutions. Currently, many modular factories have not fully integrated the various robotic or automated systems into their production environments; instead, these systems operate independently of one another. Robotic systems such as robotic reinforcement tying, additive robotic fabrication, and laser scanning-based dimensional inspection[5], [9], [13] all perform well at one or more specific production stages, but none of these are currently fully synchronized across the entire modular housing production line. In addition, interoperability between Building Information Models (BIM) and robotic control systems is still a significant technical hurdle, with design to manufacturing workflows usually requiring significant customization and calibration between the required systems[8], [11]. In an economic context, the high initial capital investment in robotic equipment, digital infrastructure, and workforce training continues to constrain robotics adoption; this is particularly true for factories producing lower volumes[1]. Although automated processes have the potential to reduce material use as a result of better design and manufacturing methods, the environmental benefits must also consider the amount of energy consumed and the embodied carbon associated with robotic manufacturing[9]. Digital twin technology has been used to increase the traceability of the lifecycle and the integration of the fabrication and inspection phases of production; however, there are currently no industry-wide standards for digital documentation and lifecycle assessment[17]. There are also many organizational barriers to the acceptance of digital twin technologies, including the need for workers to improve their skills for BIM-based design, robotic programming, and digital data management and resistance to making long-term investments in automated manufacturing[1], [11]. In addition, safety regulations and certification procedures currently exist for manual construction and have not yet been adapted to the collaborative human-robot production environment, which will limit the potential operational efficiency of automated inspection and fabrication systems. Therefore, for automated robotic modular housing to be adopted on a larger scale, there must be advances in technology integration, the development of new economic models, increased workforce training, and new regulatory frameworks.

10 Future Trends and Research Directions

Future advancements in robotic production of precast modular housing will shift from robotics that perform only isolated tasks in precast construction to cyber-physical production systems that integrate all stages of production into a single, coordinated system. The current robotic applications in use today, such as reinforcement tying, additive manufacturing, and dimensional inspection, operate at a single stage of production and are not currently integrated into a synchronized system[5], [6], [9]. As a result of these facts, future research should focus on integrating these technologies through building information modeling (BIM)-based design-to-manufacturing systems. This integration will create a direct connection between the digital model that is formulated throughout the design phase and the robotic implementation of precast construction by providing real-time feedback from sensors that are placed on the manufacturing equipment used to produce the precast modules, thus enabling adaptive control of the manufacturing process[11]. Moreover, digital twin technology will assist in integrating inspection data, manufacturing parameters, and assembly records, thereby facilitating predictive quality control and continuous improvement of the manufacturing process[17]. Beyond machine perception, such as reinforcement identification, point cloud classification of reinforcements, artificial intelligence will advance into higher levels of decision-making systems that can optimize production schedules, forecast equipment failures, and automatically modify manufacturing conditions in real time[1], [5], [7]. In order to facilitate circularity and robotic modular construction, it will be critical to develop connection standards and protocols for integrating virtual building data (BIM) that enable the automatic disassembly and reuse of modular parts[10]. Finally, developing applicable regulatory standards, implementing carbon accounting frameworks and providing construction workers with a robust education and training program will be paramount to support the widespread adoption of robotic modular housing.

11 Conclusions

The use of robotics and automation is slowly converting precast modular housing into an entirely digital manufacturing process. With factory-controlled manufacturing processes, robotic fabrication, automated inspection, and BIM-driven workflows, there are opportunities to improve precision, productivity, and consistency in production. The implementation of these technologies can also lead to improved safety, reduced material waste, and enhanced lifecycle tracking of modular components; however, large-scale adoption remains limited, in part due to multiple barriers to entry, including significant capital investments, limited interoperability between systems, worker skill requirements, and evolving regulations. Eliminating these barriers will be key to establishing fully automated modular manufacturing facilities. In summary, robots and automation processes provide a major avenue for developing scalable, efficient, and sustainable industrialized housing production.

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