

Review

Challenges of Robotic Technology in Sustainable Construction Practice

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Abstract: This review discusses new technologies in the construction industry, such as digitalization, automation, and robotization, which have an impact on improving sustainable construction in the digital transformation in the era of Industry 4.0. This review focuses specifically on the impact of robotic technology on the triad of sustainable construction: economy, environment, and society. Current trends in the construction industry related to common data environments (CDEs), building information modeling (BIM), construction robots (CRs), and bricklaying robots (BRs) are highlighted. Robotics technology used throughout the construction industry in a sustainable construction context is presented, including bricklaying, plastering, painting, welding, prefabrication, and material handling. New trends in robotics technology with respect to robotic bricklaying are presented, and the first mobile robotic bricklaying system (RBS) in Poland, which was designed, modeled, simulated, and built from scratch, is distinguished. The RBS was tested under laboratory conditions and verified on the construction site. Included are the main factors that make it impossible to spread robotic technology on construction sites, and furthermore, many solutions are proposed to problems associated with the robotic transformation. The discussed robotic technology is not limited only to a purely technical approach but takes into account challenges corresponding to the circular economy.

Keywords: sustainable construction; common data environment; building information modeling; robotic technology; construction robot; bricklaying robot



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1. Introduction

Sustainable construction comprises several different activities that aim to reduce the negative impact of construction on the environment throughout its lifecycle, from the preparation of the project to the construction process to the operation. The concept of sustainable construction covers many aspects, including social, ecological, and economic aspects. The concept of sustainable development satisfies the current development aspirations in a way that will enable subsequent generations to achieve the same goals. A special feature of sustainable construction is the interpenetration of various fields and sciences, including social and natural, to shape the appropriate future of subsequent generations and to care for natural resources.

The main obstacles to the development of sustainable construction in Poland are the high prices for appropriate building materials and the low awareness of the benefits of sustainable construction. The biggest problems are an insufficient number of people qualified to conduct and supervise sustainable construction projects, systemic gaps in the tax law that would support this type of initiative, and the lack of the translation of the costs of construction investments into the price of real estate.

The current agenda of the World Green Building Council (WGBC) assumes the complete decarbonization of the construction sector by 2050 [1]. Experts from all over the world agree that building a property with a zero-energy demand, and consequently no CO₂ emissions, is usually impossible. Therefore, passive or energy-saving projects that

draw energy from renewable sources during each stage of construction are optimal for achieving these goals. These activities, carried out on a global scale, have a positive impact on the natural environment. To achieve these goals and properties, developers must use environmentally friendly materials that are natural or fully recyclable. For example, the use of aluminum systems in a project allows for the creation of a modern and durable building architecture.

According to the Global Status Report for Buildings and Construction [2], cities are responsible for 80% of global greenhouse gas emissions, while the construction and building industries contribute to 36% of the total energy consumption and 39% of the CO₂ emissions associated with energy use and production. The production of building materials, such as steel, cement, and glass, is responsible for more than 10% of the total global energy consumption and carbon dioxide emissions related to manufacturing processes. The construction sector generates a substantial amount of waste and pollution, consisting of residues derived from the manufacture of construction materials and demolition debris.

In the global construction industry, the trend to certify buildings in terms of their impact on the environment is becoming increasingly popular. Multi-criterion certificates for “green” facilities are voluntary templates of solutions to be used in the project. In this scheme, independent entities evaluate various buildings of the same type to choose the correct template for the new construction. They discuss the environmental aspects, the use of secondary raw materials, and how the entire construction process will affect the local infrastructure and society.

The following certificates raise the rank of the investment and confirm the property of the building:

- The Building Research Establishment Environmental Assessment (BREEAM) is a highly sophisticated scientific approach widely recognized for evaluating and certifying sustainable buildings [3]. BREEAM-certified criteria contribute to improving the efficiency of constructed structures in all stages, including design, construction, use, and renovation. The BREEAM addresses the construction and sustainability issues faced by large contractors, developers, architects, and consulting firms;
- The principles associated with the construction of an environmental assessment were established in the United States, specifically based on Leadership in Energy and Environmental Design (LEED) certification [4]. Currently, these principles serve as the most widely used green-building rating system in the world. The LEED certification system offers a structure for the construction of environmentally friendly, energy-efficient, and financially viable green buildings that provide advantages to the environment, society, and corporate governance. LEED certification is widely recognized as a symbol of the successful implementation of sustainable practices and is endorsed by numerous dedicated individuals and organizations in the industry that are actively leading the way toward a more sustainable market;
- To ensure the practicality and comparability of sustainable construction, the German Sustainable Building Council (DGNB) has created its own certification system [5]. The DGNB system has undergone constant development since 2009 and is now widely regarded as the most advanced system worldwide to evaluate sustainability. It has also gained international recognition as the standard for measuring sustainability. The DGNB Certification System can be used for various types of structures, including buildings, districts, and interiors. As a tool for planning and improving efficiency, it enables all individuals involved in the construction to achieve a comprehensive level of sustainability and quality;
- The French Green Certification (GC), sometimes called High Environmental Quality (HEQ) certification, is a visible sign of excellence that shows the commitment of a building, neighborhood, or infrastructure to meeting the sustainability challenges of a city. Whether it is a residential or commercial structure, this certification guarantees that the project meets the necessary standards and expectations for environmental sustainability [6]. The HEQ certification represents a harmonious combination of

environmental sustainability (including energy efficiency, carbon footprint reduction, water conservation, waste management, and biodiversity preservation), improving living conditions and economic prosperity, achieved through a comprehensive and diverse set of criteria. Regardless of location, HEQ certification serves as a strategic plan that ensures the management of expenses and project schedules during construction, the management of costs and risks during operation, and the ability to differentiate oneself in terms of renting or selling;

- The WELL Building Standard (WELL) is a roadmap for creating and certifying spaces that advance human health and well-being in 10 concepts, including air, water, thermal comfort, light, movement, nourishment, sound, mind, community, and materials [7]. WELL certification is ideal for implementing GC within a single building or asset. Through the WELL program, organizations can monitor the ongoing building performance and gather feedback from employees to take a data-driven approach to their health and wellness efforts. The WELL certification metrics advance environmental, social, and governance (ESG) reporting efforts.

Both the BREEAM and LEED building assessment systems are popular in Poland.

The main attitudes and concepts of sustainable construction are intelligent and sustainable growth, the durability of manufactured products, the circular economy, the reduction in greenhouse gas emissions, improvements in energy efficiency and the use of natural resources, the reduction in and rationalization of consumption, and the improvement of the quality of life of society [8–10]. Sustainable construction applies to all phases of the lifecycle (from cradle to grave), such as the product phase: the supply of raw materials, the production of the product, transport to the construction site, and installation; building phase: use and operation; and liquidation phase: demolition and development aimed at the consumer. Sustainable construction aims to construct homes and infrastructure that are of higher quality and more affordable. It also focuses on reducing the environmental impact of construction by decreasing the carbon footprint and promoting a greener building environment. Sustainable construction includes three basic pillars: the social, economic, and ecological. The triad of sustainable development is presented in Figure 1. The environmental pillar includes protecting the environment, minimizing destruction, reducing toxic emissions, managing resources, maintaining stability, and minimizing pollution. The social pillar includes indoor air quality, safety and health, risk management, design requirements, functionality, aesthetics, and labeling. The economic pillar includes quality, adaptability, constructability, durability, affordability, and waste minimization.

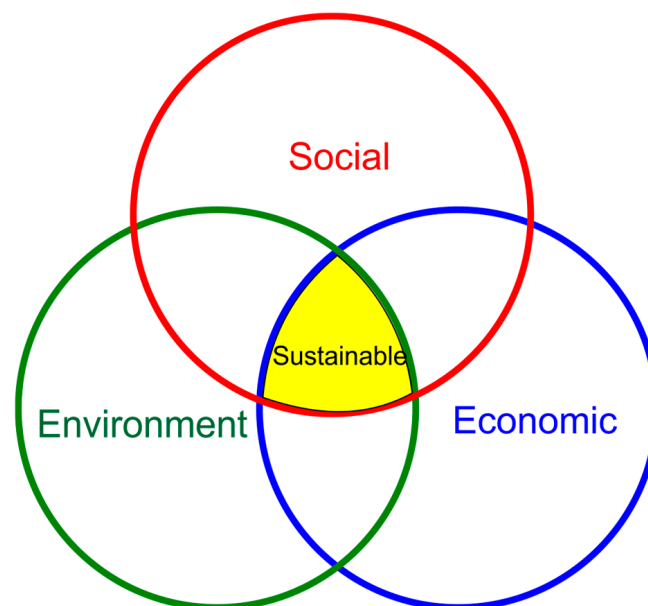


Figure 1. Triad of sustainability development.

The following are concepts in the design of sustainable construction:

Environmentally friendly construction

Environmentally friendly construction focuses not only on materials, waste reduction, and energy savings but also on the future and the entire period of use and maintenance of buildings, as well as the possibilities of adaptation and rehabilitation, or reducing the need for demolition;

Energy-efficient construction

When building infrastructure, it is important to consider the energy efficiency of the construction technologies and equipment used;

Sustainable building materials

In addition to considering the amount of energy consumed, it is also crucial to consider the longevity and environmental impact of the materials used. Sustainable building incorporates environmentally friendly materials such as bamboo, straw, wood, hemp, and stone. It also involves the use of green concrete, low-VOC paints, energy-efficient fixtures, low-e coating halogen-filled glass, and thermal insulation. These materials are preferred over traditional ones because they are easier to produce and have a positive impact on the environment by reducing energy consumption;

New sustainable construction techniques

Sustainable building practices incorporate modern methods such as prefabrication, modular construction, automation, and roboticization, resulting in less labor, energy, and waste. In addition, these practices reduce the reliance on heavy equipment that releases harmful pollutants into the environment;

Reducing networks

Construction sustainability can be obtained by preventing the need to redo the work on site, resulting in a reduction in the material and energy waste. Networks are the main hindrances to construction productivity;

Community collaboration

Sustainable construction should implement projects in cooperation with the communities that live and work there.

2. Materials and Methods

The construction industry is beginning to adopt digital technology and automation on a large scale. The use of new technologies in construction helps simplify the construction process and improve efficiency in terms of costs. The introduction of technological advancements has a beneficial effect on the financial aspects of companies. The company's competitiveness in the market is boosted thanks to the implementation of new technology, leading to the successful acquisition of project tenders. The process of implementing new technology is known for its superior efficiency. The main objective of the study mentioned in [11] was to investigate how green knowledge management (GKM) impacts green technological innovation (GTI) and sustainable performances within construction companies. The research also examines how artificial intelligence (AI) can impact the connection between GKM and green human capital (GHC). The aim of the research carried out in reference [12] is to assess how digital twin technology can be incorporated into the different phases of construction, from the initial design phase to the actual implementation of the project. Adopting digitalization and adapting to Industry 4.0 can greatly enhance the effectiveness and output in the construction sector by promoting more innovative practices and better collaboration, ultimately decreasing information gaps and data inconsistencies. In [13], a new method is introduced called the fuzzy decision-making trial and evaluation laboratory (fuzzy DEMATEL) combined with social network analysis (FDSNA). FDSNA reveals the cause-and-effect connections between the main obstacles that prevent the use of blockchain

technology in a sustainable construction project. It also identifies the most crucial obstacles by analyzing their complex interconnectedness in closely related contexts.

2.1. CDE Platform

The existing solutions enable construction companies to significantly reduce the amount of waste, limit the carbon footprints of construction sites, and optimize the use of materials. These solutions allow for the collection and management of environmental data on construction sites. CDE digital platforms implement data digitization and analysis processes that are essential for modern construction [14]. They provide engineers with tools to manage the construction process and project managers with tools to coordinate investments. According to the Colliers data on the environmental, social, and governance (ESG) technology at construction sites, construction companies appreciate CDEs primarily for the possibility of efficient decision making, the security of the data storage, electronic document circulation, clear communication, and saving time on administrative work. Despite these advantages, only 32.4% of construction companies have implemented the CDE platform or a similar electronic information management system on their construction sites. According to estimates, 33.8% of companies do not currently have these tools, and 23.9% are currently in the process of implementing them. In [15], the impact of CDEs on the efficiency of construction projects and the possibility of their implementation in real projects were observed. Implementing a CDE in the construction industry for small and medium enterprises appears to be crucial to organizing and managing the flow of important information within construction projects effectively [16]. In [17], the results of a survey conducted in the province of Quebec are discussed to understand the rate of adoption and implementation, the barriers and challenges, and the current trends of CDEs. In the study conducted in [18], the authors examined current methods of utilizing a CDE to manage information during the lifetime of a built asset. This investigation involved a thorough review of the existing literature, as well as an empirical study. In [19], the main objective was to establish the minimum requirements for a CDE and to describe the functionality of the VIRCORE collaborative platform, which was created to maximize the possibilities of BIM.

In the context of sustainable construction, information technology is crucial in the shift from traditional methods to advanced robotic technologies [20]. A progressively popular solution in the field of construction project management is the CDE platform, which is an innovative way to effectively manage information. A CDE is a tool that allows for the efficient gathering, organizing, and disseminating of information related to a building project. It is a type of digital database that allows all the people involved in a project to work together, exchange information, and update in real time. CDE platforms combine different types of data, including designs, drawings, schedules, documents, material details, and more. This integration helps to improve communication and productivity during the construction process. CDE platforms help make processes more efficient and improve communication. However, the implementation of these remedies is accompanied by specific obstacles, including the requirement for initial capital, the integration of technology, and concerns about protecting sensitive information. Despite the challenges, the advantages of CDE platforms appear to exceed them, making them an optimistic resource for the construction industry to improve effectiveness and creativity. Figure 2 shows the concept of the CDE platform.

Benefits of computer-aided design and engineering (CDE) platforms in the construction industry include the following:

Improved communication

CDE platforms encourage openness and efficient communication among all the individuals involved in the project. With the presence of a single primary data repository, people can conveniently retrieve up-to-date information, solving the issues of outdated data and incorrect information. Users do not need to manually notify others about any changes made when introducing a new file to the system, as the process occurs automatically;

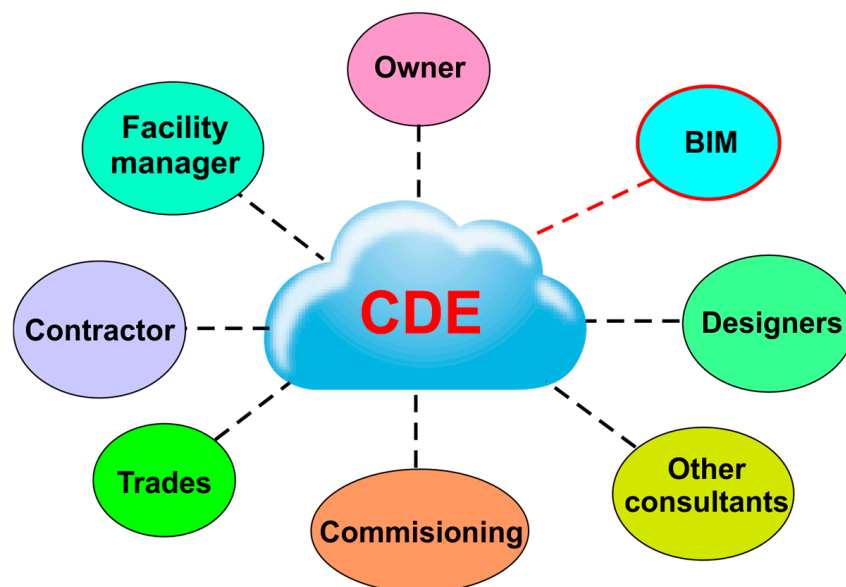


Figure 2. Concept of the CDE platform, in which BIM was distinguished.

Effective document management

A CDE allows for the efficient control and organization of project documents. Having all documents in one place simplifies the task of monitoring revisions, managing permissions, and performing documentation audits. As a result of this, individuals with database access can easily verify the most recent edits and examine past versions of documents;

Increased productivity

CDE platforms improve productivity by simplifying the process of information exchange. The collaboration of project participants makes it convenient for them to work together, resulting in the faster and more efficient completion of the project stages;

Better risk management

A CDE improves risk management by closely observing the project progress, detecting possible risks, and quickly adapting to new circumstances. Any deviations from the usual are instantly identified and visible in the system.

Challenges that come with the implementation of CDE platforms include the following:

Initial investments

The creation of a CDE platform requires the acquisition of initial financial and time resources. Construction companies must allocate resources to train their staffs, acquire suitable technologies, and adapt to the latest work model;

The need for technology acceptance

Certain companies may face challenges when adapting to emerging technologies. It takes time and employee training to embrace the new work model and utilize the CDE platform. In certain situations, particularly in companies that already have IT systems in place, it could be difficult to incorporate the CDE platform with the existing solutions;

The need for user education

Implementing the CDE platform requires educating all the people involved in the project. Understanding the characteristics, advantages, and regulations that govern the use of the CDE is vital for its effective implementation in practice.

2.2. BIM Technology

For newly designed buildings, the most important thing is a holistic and comprehensive approach, understanding the needs of the investor and current and future users, as well as the context of the construction site. The basic solution is building design using BIM technology [21]. BIM offers enormous possibilities for building analysis and estimates of the materials used, among its many other possibilities. In recent years, this technology has also been appreciated by developers who see the savings and simplifications that appear at the construction stage and therefore order projects modeled with BIM. BIM technology effectively aids in the implementation of sustainable design in architecture. The use of robots in the BIM process has the ability to increase its speed and improve productivity in construction. Robotic automation can accelerate the design process using building information modeling (BIM) technology. BIM requires a structured approach that involves planning, preparation, and execution, all of which need to be performed progressively. Building information modeling (BIM) greatly improves the process of planning, designing, constructing, and managing construction projects. It is a concept aimed at digitally transforming the construction industry and has a tangible influence on sustainability.

BIM can be implemented in the following stages of the project:

Pre-Design/Planning

This stage, also known as the pre-conceptual stage, is extremely important because it involves considering numerous long-term plans and decisions that will impact the construction project;

Design

This stage uses BIM and CAD software (Autodesk Revit ver.2023) to develop intelligent, inclusive, precise, and adaptable designs;

Construction

This stage maintains the progress of the construction process and ensures that the design aligns with the actual structure;

Operations and Maintenance

This stage measure helps to avoid and rectify various maintenance problems and evaluate the assets of the building.

The advantages of BIM include the following:

1. Sustainability is facilitated by BIM, which is crucial to addressing the design process in construction. Through environmental analysis, one can determine the best strategy to improve energy efficiency, waste management, and water savings;
2. The use of BIM enables construction projects to be prepared more quickly and the pre-construction stages to be carried out more efficiently. BIM enables faster planning, simpler management, and faster project execution;
3. BIM aids in the integration of the diverse individuals involved in a project, reducing fragmentation and misunderstandings in the processes;
4. BIM enables the identification of threats and potential damage in construction with greater ease and speed than traditional methods;
5. To fully utilize the extensive range of improvements that this BIM offers, it is necessary to invest in the necessary equipment and resources.

Because BIM increases the effectiveness of training, the precision of planning, and the visibility of threats, workers are better prepared for their work and can quickly recognize health and safety threats. BIM can analyze each specific task and determine the safest method for its execution. BIM has been proven to improve efficiency in the construction industry by reducing errors, completing projects faster, and identifying potential improvements in certain areas that can reduce expenses. BIM cost estimation has revolutionized the construction industry. Previously, contractors relied on two-dimensional drawings to assess the cost of a project. This approach was frequently unreliable because it was

difficult to collect all the required data from the illustrations. BIM cost estimation changes conventional methods by enabling contractors to continuously update cost information in real time within the BIM model as the project progresses. In this manner, the designer has a clear view of the precise cost of each individual component, including the smallest detail. Having this level of information is extremely valuable in order to ensure that a project does not go over budget. BIM cost estimation has brought about a significant change in the construction sector, is rapidly becoming the norm for estimating project expenses, and is gaining popularity as an effective tool in construction management. BIM enables managers to develop a virtual representation of a construction project, integrating information regarding various aspects, such as the size of the site and the materials used. Subsequently, this model can be used for a variety of evaluations and analyses, including identifying possible issues and evaluating different construction choices. Furthermore, BIM has the ability to produce comprehensive guidelines for carrying out the project. Therefore, construction managers are recognizing that BIM is indispensable to guarantee a seamless and triumphant construction project. Figure 3 shows the lifecycle of the BIM construction project.

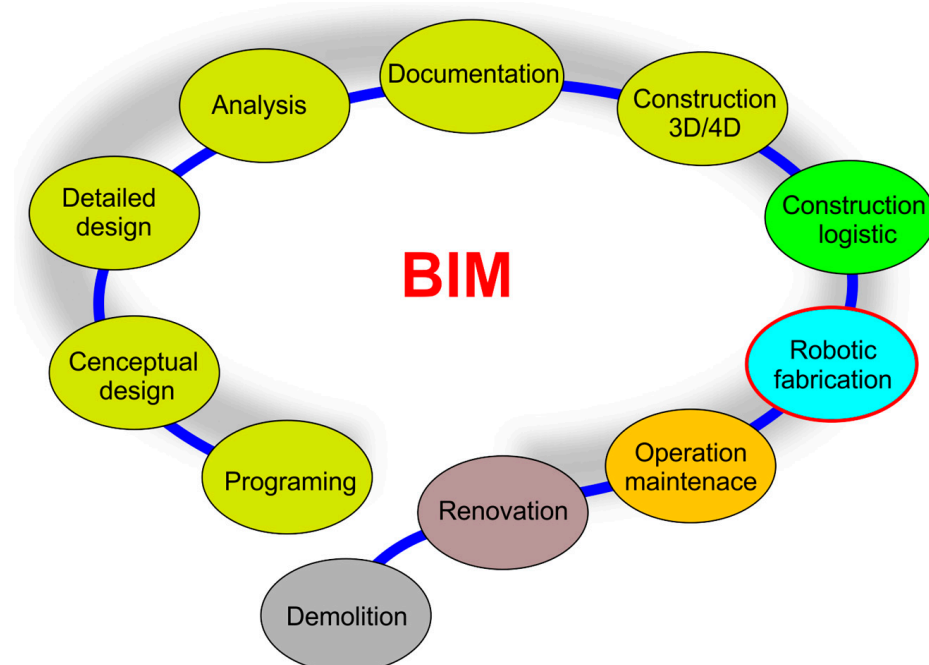


Figure 3. Lifecycle of the BIM construction project.

The combination of BIM and robotics is changing the construction industry significantly because robots are capable of enhancing productivity, minimizing mistakes, and improving safety in construction locations. The sustainable future of construction depends on the integration of BIM and robotics. The availability of 3D and 4D (time) information models in BIM promotes the robotization of construction sites by making all the design information and data collected on the site available to the construction robots in real time. As a result, the quality of the planning, construction, and maintenance processes increases, while the execution times decrease. In [22], the BIM-driven computational design for robotic programming is presented. The computational design environment utilizes BIM input models, the robotic interface, and tool-center-point (TCP) tracking. In the study [23], a system is proposed to plan coverage paths that use BIM and robotic configurations for indoor robots. In [24], a software platform is proposed for the retrieval and analysis of data from BIM models, and for their efficient use during various stages of the robotic construction process using concrete 3D printing. In [25], a BIM-based robotic model is proposed to build brick assemblies that contain all the information required for robotics

planning using the standards of the industry foundation classes (IFCs). The IFCs are a widely accepted norm in the construction sector that facilitate the exchange of information between different software applications. The authors of [26] introduced a model of a robotic operating system called the ROS, designed specifically to create plans to paint the insides of walls. This research expands the use of BIM by integrating robot task planning and creating specific tasks on a construction site. Conventional BIM does not contain knowledge of the relationships between different pieces of information; therefore, it is supported by process information modeling (PIM), which allows smooth real-time data transfer and exchange, as well as promotes seamless and constant data sharing [27]. The architecture, engineering, and construction (AEC) industry has seen a consistent increase in the use of BIM models, automation, and robotics. In [28], a quantitative and qualitative review is presented to explain the impact of the development of BIM models in construction robotics. The results of the review in [29] demonstrate that computational design (CD) can act as a bridge between BIM and robots.

BIM is becoming a tool for effective project management and safety guarantees for construction site workers. Although the benefits of BIM are obvious, more than half of the respondents (53.4%) of the Colliers survey indicated that they do not use BIM technology for design in their companies. To date, BIM has been used more frequently in the office sector and in the construction of multifunctional complexes, where 63.6% and 57.1% of respondents stated that most investments are made using this technology. However, in the housing sector, only 10% of the representatives of the companies in this segment claimed that their companies build according to designs made using BIM technology.

Construction projects can be visualized and implemented in a new way by integrating VR and AR technologies with BIM models. The use of 360-degree cameras allows for the accurate tracking of the construction progress and the identification of the potential causes of future problems. A digital image of the structure can be superimposed directly onto the actual construction environment, which not only enables more the effective coordination of work but also reduces potential construction errors. However, the data show that only 35.2% of construction companies use these technologies on their construction sites, while 53.5% still do not use VR or AR. VR and AR have the ability to simulate high-risk tasks to train newly hired workers, equip them with the skills to handle complex machinery, and teach them about emergency protocols and safety precautions. Thanks to VR and AR, the implementation of the project becomes more interactive and precise, which is crucial, especially for complex construction and installation elements, for which the risk of collision is the highest.

Construction projects can be visualized using the following robots:

1. Scanner robots, which were created to perform the horizontal and vertical scanning of buildings [30]. This information has the potential to be beneficial during the design phase and in future maintenance plans. They have a Wi-Fi connection, a local positioning system (LPS), and digital cameras that can capture pictures and videos and allow them to see the current state of the building;
2. Robots for inspection and monitoring, which are equipped with measuring tools and cameras that are used to inspect the structure and monitor the progress of the construction work [31]. They can assess the state of buildings, bridges, or other construction infrastructure and detect potential problems in areas that require maintenance, repair, or replacement.

2.3. Current Trends in Construction Robotics

The main factors that make it impossible to spread robotic technology on construction sites are the following:

1. High variability in the topography and location of the building;
2. The construction site is not ready for integration with robotic technology;
3. The level of preparation for and use of IT and digital systems on the construction site is low;

4. There is a shortage of qualified construction workers to operate and maintain the robotic station;
5. The unit cost of a robotic bricklaying station is high;
6. The approach of engineers, construction workers, management staff, stakeholders, and customers towards innovative robotic technologies is skeptical (a strong tendency to maintain established practices);
7. Supply chains of construction materials that are not adapted to robotic brickwork would create complexity;
8. There is a diversity of regional construction markets, labor and material costs, and legal regulations.

The construction industry is currently experiencing an increase in robotics-related trends [32], including the following:

1. The application of 3D printing to additive construction manufacturing, which can rationalize resource consumption and customize products to meet specific requirements;
2. BIM integration, which will lead to the robotization of construction sites by allowing construction robots to access all the design information and data collected on site in real time;
3. The integration of AR and VR, which will improve construction technology strategies and allow for the effective remote operation of robots;
4. Automation, digitalization, and robotics, which are key enablers in the circular economy in the construction industry, moving from a linear consumption model (use–consume–dispose) to a circular one (use–recover–recycle).

Furthermore, four investigations have been proposed [33]:

1. A comprehensive integration of BIM and robotics;
2. Robotic fabrication performed on site;
3. The use of deep learning to adapt to flexible environments;
4. The collaboration of robots at the highest level.

The construction industry, a major global resource consumer and waste producer, contributes significantly to greenhouse gas emissions and environmental damage. The traditional linear models of resource use are no longer sustainable. A circular economy contributes to the sustainability of construction, as the products and materials circulate through processes such as reuse, renovation, regeneration, and recycling [34]. Implementing the principles of the circular economy in the construction environment requires transformative changes in design, construction, operation, and decommissioning. Collaboration with diverse stakeholders, including policymakers, regulators, clients, and users, is essential.

The application of a circular economy in the construction industry requires solving many problems associated with the robotic transformation, such as the following:

1. The main challenges and advantages of the circular construction economy;
2. Strategies for designing buildings and infrastructure that are adaptable to the circular construction economy;
3. The potential of digital technologies to improve the circular construction economy.

In the circular economy, the construction industry must fulfill the following tasks [35]:

1. The assurance of supply chain sustainability and the collection of construction and demolition (C&D) waste;
2. The implementation of appropriate separation and recycling technologies;
3. The enforcement of political, economic, and management instruments;
4. Productivity by increasing the quality control of recycled products and their intended end use;
5. Economic feasibility, business case, commercialization, and employment generation.

The integration of BIM and robotics means a symbiosis between the digital system and the robotics capabilities that unlocks the potential for productivity, efficiency, and safety in construction. Robots can be programmed to follow BIM data, allowing them to perform precise and automated tasks such as masonry, pouring, concrete, and moving materials. Robots have great potential for widespread use in the AEC industry. This is already the case in prefabrication, but it is still limited to construction sites [36]. By using the virtual scanning process and comparing the objects found in the BIM model, companies can best match the objects at the construction site [37]. The BIM interface enables a two-way connection between the BIM objects and the robotic system; in particular, it may concern the following information [38]: information on the geometric description and location; information on the construction scheduling, phasing, and process; information on stored metadata that semantically define the objects and areas of the environment. Architects and designers use various BIM-related programs. Autodesk Revit is an established BIM design software that enables users to create, edit, and view building models in a three-dimensional environment. It is one of the most popular BIM software programs on the market and is used by BIM architects, BIM engineers, and construction professionals around the world. In addition to Revit, Autodesk also provides the Autodesk Construction Cloud to support the implementation of BIM projects. In [39], Autodesk Revit ver.2023 modeling software was used within the BIM framework for structural design. Architecture, engineering, and construction professionals can improve project communication and coordination with Revizto, a cloud-based BIM solution. Dalux is a cloud-based application that can be used as BIM software to help manage construction projects. Dalux makes it possible to manage 2D and 3D models and to work with other users to manage projects in real time. Autodesk Revit includes features such as a 3D design mode, library management, company settings, and custom label design. Dalux is known for its service coordination, user-friendly, cloud-based, and real-time communication functionalities. When comparing Autodesk Revit with Dalux, factors such as scalability, customization, ease of use, customer support, and other key factors are important. The benefits of Autodesk Revit for virtual building design include collaboration with other design applications, such as Dalux and ProDesign.

3. Construction Robots

In recent years, the construction industry has embarked on an unprecedented technological revolution based on CRs, which will lead to new dynamic developments in construction processes and infrastructure [40]. The use of robots in the construction industry has an immense capacity to improve productivity, effectiveness, and adaptability in manufacturing. It can be applied to various tasks, such as laying bricks, plastering, painting, welding, producing building components and modular homes, handling materials, printing 3D homes, and creating unique structures. Robotization can be used to create more economical buildings, reduce waste in the face of environmental regulations, and improve quality and consistency. This is important, considering that up to one-quarter of materials delivered to a construction site leave the site as waste. Due to sustainable construction, waste can be eliminated at the beginning of a project through efficient building design and construction processes. Robots can increase the safety on a construction site by handling large and heavy objects, reducing the operating costs in dangerous environments and introducing innovative and safer construction techniques. The use of robots to perform monotonous and hazardous tasks, which humans are less inclined to undertake, can address the shortage of labor and skills in the construction industry. This can also make the construction industry more appealing to young people. Robotization results in faster, more cost-effective, and environmentally friendly development while addressing the lack of manpower. Labor shortages in the construction industry are becoming a growing problem in the European Union (EU), with young people not pursuing a career in construction because it is a dangerous profession. The construction industry requires robots to keep up with the challenges of urbanization and climate change.

The construction industry has witnessed an increase in the adoption of robots in recent years due to various factors, including the following:

Increased efficiency

Robots, unlike humans, have the ability to work tirelessly and without becoming tired, allowing faster progress on construction schedules and timely project completion;

High precision

The precision and repeatability of robots are high due to their programming, guaranteeing top-notch performances and the precise completion of tasks, leading to a more polished end result;

Greater safety

According to a report by the National Safety Council (NSC), the implementation of robots in the construction sector significantly improves the safety conditions at work [41];

Reliable workforce

Robots have the ability to perform tasks without interruption despite challenging working conditions, such as intense temperatures, heavy objects, and elevated heights;

Sustainability

Robots play a crucial role in promoting sustainable development in the construction industry and protecting the environment. They achieve this by optimizing material usage, minimizing waste, and promoting energy-efficient manufacturing processes;

Adaptability

Construction robots are becoming more and more versatile and personalized, enabling them to carry out a greater variety of chores and adjust to different construction situations;

Collaboration with humans

Construction robots, which are also known as collaborative robots, or cobots, are gaining more popularity because they are specifically made to assist humans in construction work. These robots are valued for their ability to improve productivity in various construction tasks without compromising safety. Cobots could revolutionize the way to approach construction materials in the future, when sustainable materials are no longer an alternative but a standard and delicacy is a paramount quality essential for dealing with less conventional yet more sustainable building blocks. Because cobots are lightweight robots, they can handle new eco-friendly materials, such as mycelium-based composites, hempcrete, or recycled plastics;

Artificial intelligence

Construction robots that incorporate artificial intelligence and machine learning have the ability to make decisions independently, optimize tasks, and improve the operational efficiency;

Printing 3D

The advent of 3D printing technology has completely transformed the field of construction by allowing for the fabrication of whole buildings through automated additive manufacturing (AM).

The development of construction robots is constantly progressing, offering more changes in the construction sector, specifically with an emphasis on sustainable construction methods. There are various types of construction robots available that vary in their designs, purposes, characteristics, and levels of complexity. There are also three different types of control for robots: remote control (also known as teleoperation), semiautonomous control, and fully autonomous control, depending on the level of control. In the study [42], the researchers examined a teleoperational control system that incorporated virtual reality (VR) for a construction robot. This system includes a teleoperation construction robot

controlled by a servo, two joysticks used to control the robot, and a 3D virtual environment. Semiautonomous robots have the ability to perform specific tasks without human intervention, but humans can supervise the construction process and handle more intricate and complicated tasks. The advantages and disadvantages of the semiautomated masonry system SAM100 were examined in a project at Auburn University in Alabama, USA, specifically at the Gogue Performing Arts Center [43]. Fully autonomous construction robots are capable of carrying out tasks without any human involvement, performing them from start to finish. These robots have highly developed sensors, control systems, and algorithms for artificial intelligence, which allow them to successfully navigate intricate construction sites, understand building blueprints, and execute construction tasks with exceptional accuracy and productivity. According to a market analysis, anticipated growth is expected in the fully autonomous construction robot industry in the near future. The review [44] explains research studies that focus on improving automation in the construction industry and recommends advances in autonomous construction machinery and robots.

The construction industry uses robotic technology to perform a wide range of tasks, for which the following construction robots are distinguished:

Bricklaying robots

These robots have the ability to automatically brick walls, facades, and other structural components [45]. Bricklaying robots have the ability to precisely place and arrange bricks, leading to faster and more precise wall construction;

Plastering robots

These robots are designed to plaster walls and ceilings on construction sites [46]. They can scan walls, apply plaster with high accuracy, maintain a constant thickness of the plaster, and reduce ergonomic problems and the costs of spraying interior walls;

Painting robots

These robots were designed to spray paint autonomously [47]. They are equipped with a 3D laser scanner capable of creating a digital model of the space being painted with the help of an operator. Once the information is uploaded to the robot's internal system, it can begin completing the assigned painting task;

Printing robots

These robots utilize additive manufacturing to create structures or parts through 3D printing [48]. These designs can be created digitally to construct entire building components or structures by adding layers one by one, quickly and accurately, while minimizing the amount of wasted materials;

Demolition robots

These robots were specifically designed and are equipped with tools and accessories that allow them to safely and efficiently demolish buildings [49]. They have the ability to safely and quickly remove walls, floors, and other parts of a building, thereby expediting the demolition procedure while maintaining safety;

Welding robots

These robots are used for automated welding duties in construction [50]. They have welding arms or fabrication tools, which enable them to perform complex welding or assembly tasks on steel beams or structures. This guarantees durable and reliable connections with accuracy and swiftness, while also maintaining consistent quality;

Material-handling robots

These robots were created to move heavy and bulky objects on construction sites [51]. They have the ability to improve logistics operations and alleviate the physical exertion of human employees;

Robotic excavators

These robots were created to perform tasks that involve excavation and digging, such as creating trenches, laying foundations, and moving earth [52]. They possess specific tools, arms, and detectors that enable them to extract soil and dig in difficult landscapes with precision.

The use of robotics in the construction sector started in the early 1990s with the main aim of improving construction processes, improving safety, and guaranteeing the construction of high-quality structures. Currently, innovative construction robots are taking on industry challenges and making valuable contributions to the achievement of multiple Sustainable Development Goals (SDGs). Construction robots play a crucial role in the promotion of sustainable urban development and contribute to SDG 11: Sustainable Cities and Communities. The 2030 SDGs are a blueprint for achieving a better and more sustainable future. The construction industry can play a crucial role in achieving the SDGs by being more environmentally friendly, effective, and secure. This benefits not only the industry itself but also the communities it serves. In [53], robotics is capable of helping society manage multiple current and future challenges and contribute to a responsible future, as defined by the United Nations SDG initiative. A multidisciplinary analysis of the role of robotics in achieving the SDG goals is presented, focusing on economic, social, and environmental priorities. Robots have enormous potential to support the SDGs.

The initial expenses associated with incorporating robotic automation into construction activities are substantial, especially with regard to the technology investment and the adjustment to unfamiliar systems. Long-term advantages consist of significant decreases in labor and operating expenses, increased effectiveness, and the improved quality of the construction results. Bringing robotic automation into construction activities involves various factors that affect the costs, including upfront investments and the potential for long-term financial gain. The use of robotics in the construction industry, particularly in off-site construction, has been shown to significantly increase annual production rates by 52% and reduce overall costs by 21.56% [54]. This demonstrates the potential for significant cost savings and efficiency improvements. Similarly, the use of different robotic systems for activities such as improving and inspecting the quality of the location has shown a decrease in the time required for significant tasks of 57.85% and a reduction in overall labor costs of an average of 51.67% compared to manual work [55]. A large-scale research project found that although productivity showed an improvement of approximately 9.5%, the cost of construction using this method was approximately six times higher than that of traditional methods. This indicates that the initial investment costs are significant. The use of automated systems in construction can result in reduced logistics, human, and energy resources, although there may be an initial increase in the construction expenses. Using robots to paint exterior walls can improve the efficiency, decrease the need for human labor, shorten the construction time, and, consequently, lower construction expenses. However, construction robots face distinct obstacles in contrast to immobile industrial robots. These challenges include the need to navigate the construction site and operate efficiently in unfavorable conditions, which can potentially affect the cost and complexity of robotic systems in construction.

The economic viability of using robots for construction tasks must take into account all the associated costs and benefits. We can classify these costs as follows:

1. Development costs, which include the total expenditures related to manpower, resources, and infrastructure used to investigate, experiment, and evaluate the different options for robotic solutions;
2. Investment costs, which include various components, such as the depreciation in value over time and the interest paid to the investment. These costs also comprise expenses related to the acquisition of new equipment, considering its expected useful life, as well as the interest incurred in the investment. The expected lifespan of industrial robots, typically lasting 5–10 years, may be slightly shorter for construction robots that work in harsh environments;

3. Setup costs, which include the installation of the robot and the equipment that makes the robot its workplace, the running and programming of the robot, and the learning expenses of the operators. The construction robot will operate at different workstations; therefore, its setup costs will be higher;
4. Maintenance costs, which include the regular maintenance, inspection, and repair of robots and equipment. These costs are higher for construction than for manufacturing;
5. Operational costs, which include the electricity consumed for the robotic work in the construction and the transfer cost of moving robots from one workstation to another;
6. Indirect expenses, which include the adaptation of the work process to robots in the environment on construction sites.

3.1. Robotics in Architectural Construction and Fabrication

Robotics is revolutionizing the field of architecture and changing the way buildings are created and constructed. Robotic architecture and assembly robots combine robotic systems and fabrication technologies with construction and design processes [56]. The advancement of robotic technology in architecture has allowed for the construction of intricate and environmentally friendly buildings, expanding the limits of design. Designers, artists, and architects are very interested in using industrial robots for creative design. Many researchers and architects have suggested the use of robots in architectural practice, but this area is still in its early stages and needs further investigation.

The utilization of robotic technology in architectural construction and fabrication offers several benefits compared to traditional methods, such as the following:

1. Architects have the ability to create intricate and distinctive designs that incorporate complex shapes and structures that were once difficult to achieve;
2. The execution achievement of intricate designs with minimal mistakes with a high level of precision and accuracy;
3. Using robotics in architectural construction design results in enhanced efficiency and less time required for repeated tasks;
4. Robotic systems are designed to improve the efficiency of the materials used, reduce the amount of waste produced, and promote environmentally friendly construction methods;
5. Robots are responsible for performing dangerous tasks, which ultimately improves the safety of workers by minimizing the potential dangers found on construction sites;
6. Robotic fabrication has the ability to adapt to different project scales and levels of difficulty, allowing architects to experiment and explore various ideas and techniques in architecture.

In [57], the potential of architectural robotics is investigated by examining the range of design possibilities and characteristics in both academic research and real-world applications. The conclusion from this research is that the currently available software toolkits are not sufficient to enable the full use of robots in architectural practice. However, robotics and other digital fabrication tools will play an important role in the future of architectural design and education [58]. There are two main fields in which robots are being developed: digital architecture and construction sites. The architectural design of the building construction is an application of multiple-robot systems (MRSs), which are becoming more common in the research and are known as collective robotic construction (CRC) [59]. The use of robots combined with digital design tools means that new architectural aesthetics with innovative shapes and patterns have become possible. Using robots from ETH Zurich, intricate building parts made of wood, concrete, brick, and foam were used to build complex installations in Zurich, London, Barcelona, New York, and other locations [60]. The primary focus of modern architecture fabrication techniques is the use of industrial robots in off-site prefabrication processes [61]. This research demonstrated that robotic in situ production is not only a future possibility but also a reality that can be applied to tangible construction projects. The concept of design for robotic construction (DfRC) was introduced in [62], and collaborative robotic systems have been developed for the construc-

tion of load-bearing structures. In [63], a comprehensive review of the use of automation technology for structural prefabrication and construction is presented, including recent developments, challenges, and future trends. The recommended construction sequence consists of five stages that utilize robots: design, construction management, prefabrication manufacturing, autonomous transportation, and structural assembly. The analyses of automated and robotic factories on site that have been implemented to date reveal a significant difference between the technical performance achieved (the potential capability of the overall system or individual subsystems) and the improvements in productivity, economic performance, and efficiency [64]. Although developed and deployed technologies (for example, in terms of modularity, flexibility, variability, and robot-orientated design) have reached an outstanding level from a technical standpoint, their efficiency, productivity, and economic performance have remained behind the achievements in other comparable industries. The main task of [65] was the use of industrial robots in architecture and the use of robot aid for on-site fabrication. The research encompassed multiple fields of study, making the close connection and collaboration between architecture and experimental computer science highly significant. The purposes of the study were to create a mobile robotic device, develop advanced methods for feedback input, determine a location, and use digital tools to manage and execute the construction procedures. The use of a location-aware mobile robot for a discrete in situ construction process is described in [66]. A laboratory environment simulating a construction site was used to make an undulating dry brick wall using a semiautonomous system. Based on this experiment, generic functionalities of the mobile robot and its software were developed for mobile in situ robotic construction, which are presented in the following sections.

3.2. Bricklaying Robots

As the world becomes increasingly urbanized, there is a greater need for housing. However, there is a shortage of construction workers. To address this problem, robotic masonry appears to be a suitable solution to building residential and commercial buildings more efficiently and accurately while also being environmentally friendly. Robots can be useful for flexible typology bricks laid using various masonry materials. Bricklaying robots have been introduced to address the difficulties faced by the modern construction industry. These challenges allow for the maintenance of productivity and quality in construction despite acute labor shortages and a constant increase in the demand for housing. In [67], the potential of automation and robotics in masonry is investigated. A bricklaying robot can autonomously build a wall using cinder blocks. These considerations pertain to the entire process of implementing a robot, from the introduction of materials and inventory management to the construction process itself.

The main objective of the research in [68] was to examine the difficulties in adopting robotic construction technology in the Malaysian construction sector located in the Klang Valley. Data for the research were collected using a quantitative approach, in which surveys were conducted with 180 contractors based in Kuala Lumpur. Researchers obtained fifty valid responses and then analyzed the gathered information using the Statistical Package for Social Sciences (SPSS) ver.26. The survey showed that the main obstacle to introducing construction robotics in Malaysia was the expensive expenses associated with maintaining and upgrading the technology.

In [69], the case study is based on the first phase of the consultancy project funded by the Hong Kong Construction Industry Council (CIC). The CIC project provided an opportunity for cross-consultation between the construction industry and academic research, which explored the potential of implementing robotics technologies in the public housing construction (PHC) sector. The first phase of the CIC project was divided into several stages, including the initial research, a survey, a co-creation workshop, the initial design, a mock-up, and demonstration activities. Systematic decision-making tools have been developed to identify the challenges faced by the Hong Kong PHC sector. The results of the CIC project provide comprehensive guidelines that can be used as a tool to make

development decisions in the construction industry to initiate and research innovative and compatible solutions and implement robotic technologies in the future.

As part of a NKFIH grant, in Hungary [70], research was carried out to obtain better automatic bricklaying times for straight solid walls in two ways: by determining better bricklaying and by using an unconventional masonry work method. Automated masonry structures were modeled using a robot arm that moved on a linear rail. Various brick-wall-building methods were tested and analyzed to find optimal solutions for the various factors that influence the bricklaying process. The research conclusions only concerned the influence of the location of the pallets with bricks on the time of the automatic bricklaying.

The creators of KM Robotics and Wienerberger described the use of the first bricklaying robot in the Czech Republic [71]. The bricklaying robot was tested in 2013 at the GEMO a.s. construction site in Šumperk. The worker uses the tablet to designate the location to place the brick, while the robot autonomously retrieves and positions the brick from the pallet, applies the construction adhesive, and deposits it in the designated place. This means that the work of the bricklayer team can be replaced by a bricklayer robot. This robot can perform brickwork up to 10 m² per hour and up to a maximum height of 275 cm using special bricks adapted for this type of work.

In [72], a comprehensive approach to developing a bricklaying plan is introduced. This technique utilizes the IFC format, in which drawings from the BIM environment are transformed into a boundary representation (BREP) model. This process divides the object models into layers and also establishes connections between discontinuous wall axes through an orthogonal arrangement. In addition, this method involves inserting details into crucial structural points.

In [73], the design of a functional model of a bricklaying industrial robot is presented that can technically implement the entire bricklaying process. The bricklaying robotic system employs custom software that converts digital data from the BIM environment into a KRC4 format suitable for KUKA industrial robots. In addition, it improves and optimizes the path of the robotic arm's movements.

Designed by the company Construction Robotics (CR) in the United States in 2015, the semiautomatic mason (SAM) increases the efficiency of traditional masons [74]. It improves the work of bricklayers when laying bricks, which is three times faster than that of humans. Due to its many degrees of freedom, the SAM is largely flexible, independent of unevenness, and moves on the platform. The SAM bricklaying tasks can be adjusted according to the building specifications and working conditions. The SAM uses angle, speed, and direction sensors. The SAM effector is also equipped with a laser that orients it relative to the wall during brick laying and helps to determine the position of the brick laid in the next cycle. The SAM is suitable for large buildings, such as hospitals, shopping malls, and university buildings. Bricklaying work is quite time-consuming and laborious; therefore, it is an ideal field for showing off the SAM machine. The SAM can also perform more complex activities, such as building bricks by arranging them in previously programmed patterns. In the study [75], the focus is on examining how contractors perceive the implementation of the SAM as a robotic bricklayer in the construction sector in South Africa. This research explores the use of the SAM as a potential method for the introduction of automation and robotics in the industry.

The Australian robotics company FBR is introducing the Hadrian X, an advanced robotic system capable of fully independent operation, from the dynamic grasping of varying bricks to the erecting of entire structures using the precise placement of bricks according to the specifications of the 3D BIM model [76]. In 2023, FBR introduced the next Hadrian X robot, which automatically lays blocks on the wall. FBR is collaborating with M&G Investment Management to finance three new Hadrian X robots for use in the USA. The next-generation Hadrian X has set a remarkable bricklaying pace, surpassing 300 blocks per hour with cement blocks of the US standard, showcasing substantial advancements in robotic bricklaying technology. The Hadrian X uses specialist construction bonds instead of

standard mortar, cutting carbon emissions while furnishing from four to five times greater strength, increasing the durability of the building structure.

The Automated Bricklaying Robot (ABLR) developed by Construction Robotization Yorkshire is the first robot in the world that can lay any type of brick using different types of mortars [77]. It is also the first bricklaying robot that is exceptionally capable of bricking corners and vaults. The ABLR is supported by advanced control software with an interface for digital building architectural plans. Bricklaying with the ALBR system requires an employee to load bricks and mortar, remove excess mortar, and complete the lintels and points. The ABLR is integrated with material requirement planning (MRP) systems, which allow for the minimization of waste at the construction site by controlling the flow of construction materials using QR codes. The ABLR facilitates greater flexibility in the adoption of bricks to meet the architectural requirements in terms of brick shapes, bonding patterns, and texture, while maintaining quality, which is important in mass-customized housing.

Ballast Nedam is the pioneer, creating the first bricklaying robot in the Netherlands [78]. The construction of the Rotterdam low-energy project Tuinbuurt Vrijlandt utilized a robot specifically designed for bricklaying. This robot was developed by the company Ballast Nedam Development and was constructed by Ballast Nedam West. The construction industry can greatly benefit from the advanced capabilities of Ballast Nedam bricklaying robots, which can work at a faster pace, with increased efficiency, and to the benefit of the environment. Ballast Nedam invests in innovation, and the use of bricklaying robots transforms the construction site into a modern production site. The mortar is applied very precisely and is dosed. The robot uses 455 g per brick, whereas a traditional bricklayer uses 1000 g. Robotic bricklaying produces 70% less masonry material waste.

As part of the research project [79], the first original mobile robotic bricklaying system (RBS) in Poland was developed from scratch as a demonstration version. The original projects included the design, modeling, simulation, and creation of the RBS, as well as laboratory tests for robotic bricklaying and the implementation of robotic bricklaying tasks at the construction site. The RBS was created in cooperation with Kielce University of Technology, as a leading researcher, and STRABAG Ltd. Poland, as an industrial partner, which is the global leader in the construction industry. The mobile RBS is a groundbreaking solution that aims to automate the labor-intensive tasks of masonry work, typically undertaken manually by bricklayers. The mobile RBS was created with specific applications in mind, primarily for building façades and partition walls in both corporate and residential structures, as well as in industrial facilities. The mobile RBS in the demonstration version was successfully tested in laboratories and at construction sites. Currently, an industrial version of the RBS is being implemented for commercial use in construction. Figure 4 shows the 3D CAD design of the mobile RBS with the ABB industrial robot [80–82]. The mobile RBS in the Hinowa tracked undercarriage consists of an ABB industrial robot that is used as a bricklaying robot [83,84]. Front and rear hydraulic lifting and leveling modules are used to lift and level the robot [85,86]. Masonry material is taken using a robot gripper from a brick warehouse connected to a brick feeder. The control system comprises an electrohydraulic control and power module, a control panel, and a control cabinet. A 3D CAD view of the RBS, with its basic components, is shown in Figure 4. A real view of the RBS is shown in Figure 5.

Multiple types of robots from different companies have undergone assessments to choose a suitable industrial robot for the task of laying bricks. Due to the unique use of robots in construction, the main factors that affect the choice of robot are specific characteristics such as the workspace, degrees of freedom (DoFs), weight, payload capacity, maximum speed, and control type. The 6-DoF ABB IRB 4600-40/2.55-type robot was selected from the various industrial robots evaluated [87,88].

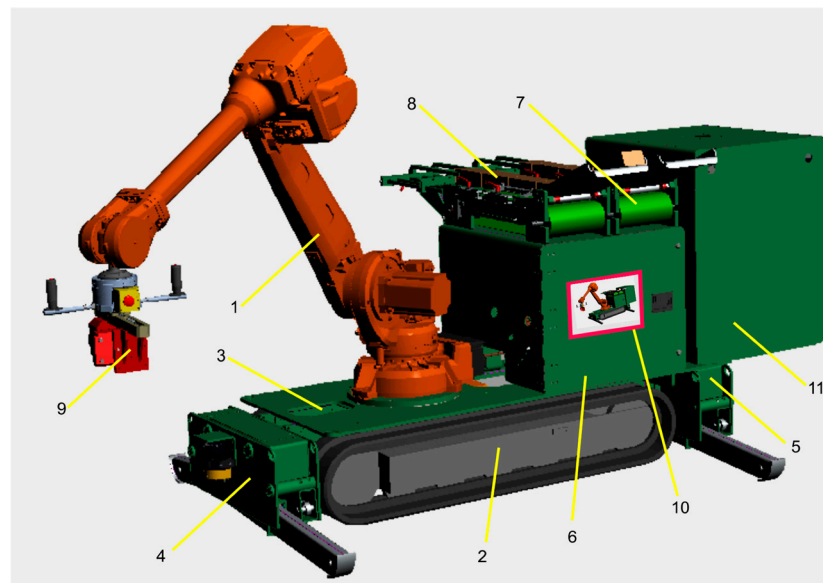


Figure 4. Three-dimensional CAD view of the RBS project: 1—industrial robot; 2—tracked undercarriage; 3—robot support frame; 4—front hydraulic lifting-leveling module; 5—rear hydraulic lifting-leveling module; 6—hydraulic power and control module; 7—warehouse; 8—feeder; 9—hydraulic gripper; 10—control panel; 11—control cabinet.

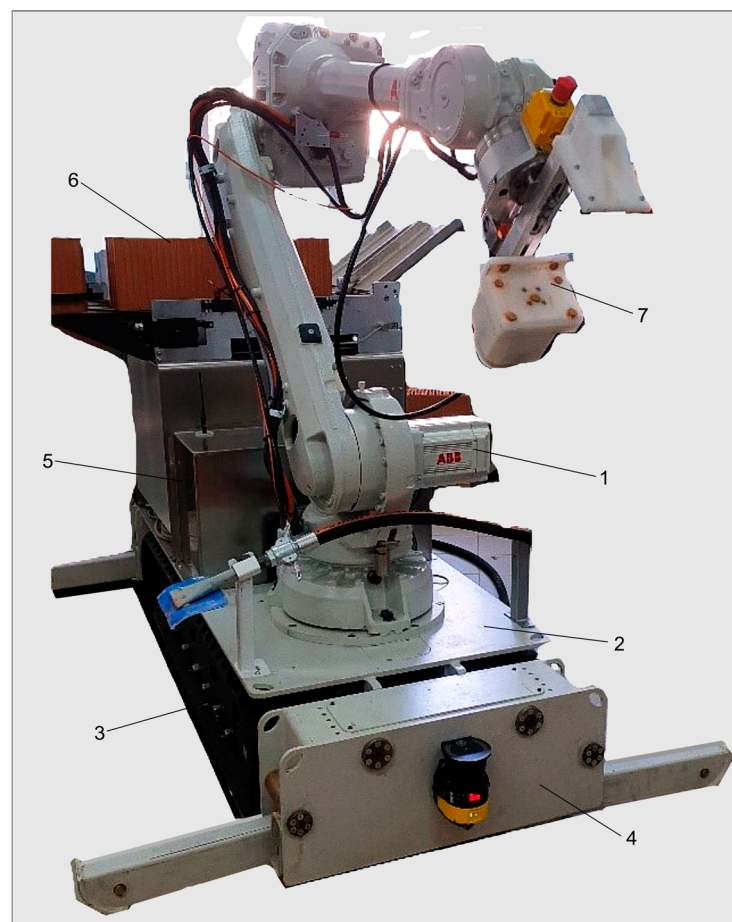


Figure 5. View of RBS: 1—ABB IRB 4600 industrial robot; 2—robot support frame; 3—Hinowa tracked undercarriage; 4—front hydraulic lifting-leveling module; 5—hydraulic power and control module; 6—brick warehouse; 7—hydraulic robot gripper.

4. Discussion

The use of robotics in the construction industry, especially in bricklaying, is consistent with the goals of sustainable development in multiple aspects. When discussing the contribution of robotic bricklaying to sustainable development, the following contributions are mainly taken into account: economic contributions, such as decreased material costs, decreased labor costs, and improved productivity; environmental contributions, such as waste minimization and the duration of the shrinking bricklaying process; and social contributions, such as improved occupational safety and health, an improved working environment, and job satisfaction. The precision of robotic bricklaying leads to the efficient use of materials and reduced waste, both of which benefit the environment and the economy. As the productivity of robotic bricklaying increases, project durations are reduced and sustainability is promoted. This implies that the construction process is more efficient and less costly. In recent years, there has been a significant increase in development strategies specifically aimed at designing automated devices that can efficiently build bricklayer walls to minimize the need for manual labor. However, the majority of these solutions require the use of heavy industrial robots and complex systems that are challenging to adjust and configure at the construction site. In [89], a prototype of an automated, lightweight, and easily programmable system that is applicable to the building of brick walls is proposed. The evaluation of this system involved the use of the Construction Automation and Robotics for Sustainability Assessment Method (CARSAM). The CARSAM offers a systematic method to analyze the environmental, social, technological, and economic aspects of sustainability in relation to advanced construction technologies. Using the CARSAM, stakeholders can gain a more comprehensive understanding of the larger consequences associated with incorporating these technologies into construction methods, which enables them to make more informed choices that contribute to sustainable development. In online surveys, the key needs of the people involved, as well as suggested approaches and plans to incorporate robotics and automation into sustainable construction in the transformative era of Industry 4.0, were identified. Surveys on construction robots were carried out, among others, in Malaysia, Hong Kong, and South Africa.

4.1. Comparison of Commercialized Bricklaying Robots

It is impossible to perform a comparative analysis of the various bricklaying robots mentioned because the availability of information about them is significantly limited and their technical, performance, and operation data are not widely published. One should consider that the design, operation, application, and use of building materials may vary for each robot.

Most often, two different masonry systems are compared: the automated SAM and the robotic Adrian X, the operations of which are as follows:

1. The SAM system seeks to streamline the conventional bricklaying process for buildings that have extensive and linear facades. The SAM system achieves maximum efficiency in bricklaying and enhances work safety by employing readily available components and a straightforward positioning, control, and gripper design. The SAM is capable of laying more than 3000 bricks per day. The SAM system is made up of a movable platform that travels on a scaffold that is already in place. It also includes a mortar dispenser and feeding system, a robotic arm with a tool to pick up and place objects, a positioning system, a power supply, and a control system. The SAM positioning system uses a laser sensor to guide the movement of the robot and its gripper. The brick-feeding system applies mortar to the brick. By using the gripper on the robot arm, the brick is picked up and positioned correctly. The SAM requires two human workers to complete the work, which involves cleaning the excess mortar off the brick, ensuring that the gaps are properly filled and sealed, and cleaning up the brick joints. The robot is assisted by human labor to load bricks and mortar into it while traveling along the scaffold;

2. The Hadrian X robotic system can significantly reduce the construction time for an average brick building. It is estimated that, in two days, the Hadrian X can build a standard one-story house, using approximately 15,000 bricks. The Hadrian X is composed of several components, including a material-feeding system, a retractable manipulator, a gripper, dynamic stabilization technology (DST), a laser guidance system, a control system, and the Fastbrick wall system. The main parts of the Hadrian X can be mounted to the standard bases of trucks, excavators, and boats. The retractable manipulator and the material-feeding system are integrated. DST is the main technology used in the Hadrian X, helping the brick gripper to react to movements of wind, vibration, and inertia proactively and in real time. The laser guidance system in the Hadrian X allows for the remarkable precision positioning of the brick gripper.

The automated SAM peaks at one brick every 12 s, which is about 300 bricks per hour. The Hadrian X bricklaying robot has hit a new speed milestone, laying 200 bricks in one hour, and will ultimately achieve up to 1000 bricks per hour. The SAM builds the wall by advancing along a track, whereas the long Hadrian X telescoping arm allows it to build from a fixed point. Unlike the SAM, the Hadrian X can lay bricks around corners and build curved walls.

If one robot can realistically lay 1000 bricks per day or 250,000 per year on a regular 250 workdays, then comparing the 250,000 bricks for a bricklaying robot with the 62,500 bricks for a bricklayer means that such a bricklayer robot equals four bricklayers and two bricklayer helpers. In today's salary terms, the cost effectiveness of using a bricklaying robot amounts to EUR 400,000 per year. A bricklaying robot needs some form of supervision, but the same supervisor can oversee a set of robots laying, for example, 5000 bricks a day. Additionally, there must be a need to add savings from invoice work, income tax, and margins. Bricklaying robots often require the use of specially adapted bricks for this type of work (Czech robot) or whole bricks (Hadrian X), as well as special bricklaying mortars. The use of bricklaying robots also has social significance because they do not want a salary increase, sick leave, or vacation, nor will they threaten to leave in order to create a competitive business.

4.2. Challenges of RBS in Sustainable Construction

The primary contributions of robotic bricklaying using the RBS are to improve the precision of bricklaying, replace humans with robots, and reduce human errors. Robotic bricklaying using the RBS is the beginning of the evolution of the Polish construction industry. The effects of using RBS robots for bricklaying are discussed, which are important in solving the existing problems on construction sites.

The scope of the robotic bricklaying performed in [90,91] was as follows:

1. The robotic bricklaying was carried out on single-layer walls with thicknesses of 8, 12, 15, 18, and 24 cm using common masonry materials, such as bricks, cellular blocks, hollow bricks, ceramic blocks, clinker bricks, and concrete blocks. Adhesive mortars were used for the bricklaying;
2. The precision and repeatability of the bricklaying were verified according to the bricklaying line determined by the cross-line laser (CLL), as well as the thickness and precision of the filling of the vertical and horizontal joints in the wall;
3. The correct operation of the bricklaying algorithm was checked using hollow bricks, brick types 1NF, 2NFD, and 3ND, as well as cell and ceramic blocks. After the wall was bricked, measurements were obtained, which showed a slight deviation of the laid bricks from the wall axis and slight differences in the widths of the vertical joints, which were within the wall deviations allowed by the National House Building Council (NHBC) [92].

The test results of the robotic bricklaying using the RBS on a construction site in a residential building were as follows:

1. The maximum robot positioning time on the bricklaying site did not exceed 4 min;
2. During the robotic bricklaying, the time required to lay a cell block with the dimensions of $24 \times 24 \times 59$ cm and a weight of 24.4 kg was 42 s (0.7 min). To build 1 m^2 of wall, seven pieces of cell blocks were needed, so the bricklaying time was approximately $7 \times 0.7 = 4.9$ min (rounded to 5 min). At the same bricklaying rate, 12 m^2 of brickwork was achieved per hour, and the cell blocks were 84 pieces. With 10 h of work per day, 120 m^2 of walls can be bricked, and with 250 days of work per year, $30,000 \text{ m}^2$ of walls can be bricked. For comparison, a bricklayer precisely and carefully laid approximately eight cell blocks of the dimensions $24 \times 24 \times 49$ cm in one hour [93]. This means that the robot bricklaying rate is more than ten times faster per hour than that of a bricklayer. Comparisons over longer periods of time do not make sense because the bricklayer will not be able to keep up with the pace of the bricklaying by the robot;
3. The deviation of the wall surface from the vertical plane was ± 10 mm at two meters, and the deviation of the wall thickness was ± 5 mm. The deviations in the dimensions of the openings (windows and doors) were $+6/-3$ mm at a width of 1 m and $+15/-10$ mm at a height of 1 m.

Compared to bricklayers, the average accuracy of robot masonry is expected to increase by more than 75%, with rework reduced by more than 80% and the reduction in hazardous tasks increasing by more than 75%.

The RBS safety devices have been verified and validated [94,95]. To assess the safety of the RBS during bricklaying on construction sites, threats resulting from the robot mobility, workspace, and movement trajectories were identified [96–98]. Risk assessment and hazards resulting from robotic bricklaying were analyzed for the robot software, teaching, operation, and starting options; operator and service access; possible robot misuse.

One primary advantage of RBSs is that they reduce human exposure to hazardous work conditions. RBSs perform safety-critical tasks precisely and consistently and rigorously adhere to the programming parameters, ensuring an accurate performance by precisely placing the bricks and mortar. The use of RBSs can improve construction site safety and reduce accidents and injuries by reducing the need for repetitive and physically demanding labor, as well as by reducing human errors and hazardous conditions. To help assess and quantify the safety hazards of human–robot interactions on construction sites, the Centre for Construction Research Training (CPWR) [99] published a report that consists of descriptions of the available robotic technologies, the factors that influence their use, as well as the current standards and procedures.

5. Conclusions

Robotic bricklaying is a suitable solution for sustainable construction due to global urbanization and the decreasing labor force on construction sites. Investment in the development of modern sustainable construction technologies such as the digitalization and robotics of bricklaying will help companies improve the quality and efficiency of their production, save time and money, and reduce pollution and waste. In recent years, there has been a notable rise in the implementation of plans to create automated tools that can effectively construct brick walls, with the objective of reducing the requirement for human effort. However, most of these solutions require the utilization of large-scale, industrial, heavy robots and intricate systems that are difficult to modify and set up at the construction site.

The main contributions of this review are its presentation of the existing solutions in the field of robot bricklaying as well as, specifically, the first original mobile RBS in Poland, which was developed from scratch as a demonstration version. A laboratory test was performed for robotic bricklaying and a robotic bricklaying task was carried out at the construction site. Original experiences in RBS design and bricklaying robot studies are presented to provide important and valuable tips for the development of robotization in bricklaying. The test results presented for robotic bricklaying using the demonstrative RBS

come from a preliminary laboratory study and on-construction-site tests. These experiences will be used to develop the final industrial version of the RBS. The results of the robotic bricklaying tests show its potential in the practice of sustainable construction in terms of reducing the amount of waste, reducing labor costs, improving working conditions, and thereby impacting the environment, society, and the economy.

The operational risks and challenges of construction robots result from the fact that, despite its promising potential, robotic bricklaying faces technological and adoption challenges that require comprehensive consideration. The initial cost barriers, the high upfront fabrication costs, and the operation of the construction robots can be barriers for small construction contractors. Concerns and reluctance have arisen among the construction workforce about job automation and their resistance to new technologies. The complexity of the design, planning, and workflow on construction sites can be a problem. Successfully embracing bricklaying robotics requires holistic operational changes, not just robotic technological insertion. Construction companies must evaluate and evaluate various strategies for planning, coordinating, and ensuring quality management to maximize the advantages gained from increased robotic productivity. It is relatively early for the implementation of robotic bricklaying worldwide; however, this review has shown that robotic bricklaying technology holds promise for sustainable construction.

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