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Implementation of an Industrial Robot in the Automation and Digitalization of Bricklaying: A Case Study

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Abstract

This study focuses on the challenges and opportunities of integrating industrial robots into robotic bricklaying systems (RBSs) for automation and digital transformation in the construction industry. A mobile RBS was designed, engineered, manufactured and commercially implemented for the first time in Poland. The RBS is designed to perform robotic bricklaying in situ in municipal, residential, and industrial buildings, where sustainable construction tasks are implemented. The details of the design solutions for the RBS, virtual simulation, and real robotic bricklaying processes are presented. The results of bricklaying using the RBS and the factors that influence the robotic bricklaying process are summarized. A 3D digital building information model (BIM) created using Autodesk Revit tools was used for simulated robotic bricklaying in the ABB RobotStudio 2025.5 program, from which they were transferred to the programming of the ABB IRB 4600 bricklaying robot. The laser programming method for the bricklaying robot, bricklaying procedures, and algorithms are also presented. The costs of human labor and robot construction were compared, and the return on investment (ROI) was calculated. RBS evaluations were performed in laboratory settings, on-site demonstrations, and commercial wall-laying in residential apartments.

Keywords: industrial robots; robotic bricklaying; automation; digital transformation

1. Introduction

Digitalization and robotization are revolutionizing the construction industry by transforming every stage of the lifecycle, from resource-efficient design and low-waste construction to precision task improvement, material handling, and energy consumption optimization [1]. Digitalization and robotization are associated with a reduction in carbon footprints, better resource utilization, eco-friendly designs, and the ability to create green designs in real time [2] and support complex sustainable projects that simultaneously address environmental issues and support the circular economy (CE) [3]. Digitalization, robotization, and automation are key to the construction industry in providing more affordable and environmentally friendly buildings, improving sustainability, and reducing environmental impact in the face of labor shortages in the construction industry. Using industrial robots for monotonous and risky construction jobs that are becoming less desirable to workers can help address labor and skill shortages while making construction careers more attractive to younger generations. Digitalization and robotization respond to current trends in the construction industry related to the common data environment (CDE) [4–6] and building information modeling (BIM) [7–9] by creating a digital–physical (D–P) feedback loop. Digitalization and robotization in sustainable construction are built on three basic pillars: social, economic, and environmental, as outlined in the sustainable development triad [10]. Extended reality (XR), as a collective

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virtual technology, supports digital and robotic technologies on construction sites [11]. XR is actively transforming construction sites by acting as a bridge between the physical world, BIM data, and robotic systems. XR acts as an interface for human–robot interaction (HRI), particularly in controlling, programming, or remotely controlling robots. Digitalization and robotization facilitate the global transition to Construction 4.0/5.0.

1.1. Global Market of Construction Robot

The Global Construction Robot Market is rapidly emerging. The market was valued between 1.4 and 5.5 billion in 2024 and is projected to grow aggressively at a compound annual growth rate (CAGR) of 15–20% by 2030 [12]. In the global construction industry, the trend of certifying buildings as green facilities in terms of their environmental impact, sustainability, and green design is becoming increasingly popular. The use of recognized global methods to evaluate and certify sustainable buildings is ideal for implementing green certification (GC) and environmental, social, and governance (ESG) reporting. Building Research Establishment Environmental Assessment Method (BREEAM) [13], Leadership in Energy and Environmental Design (LEED) [14], German Sustainable Building Council (DGNB) [15], French Green Certification (GC), sometimes called High Environmental Quality (HEQ) [16], and the WELL Building Standard [17].

The Global Bricklaying Robot Market Size, Share and Trend Analysis Report—Industry Overview and Forecast to 2032 [18] examines the segmentation of the global bricklaying robot market based on automation levels (fully autonomous and semi-autonomous) and applications (commercial buildings, residential buildings, public infrastructure, nuclear dismantling, and demolition). In 2024, the global bricklaying robot market was valued at 99.91 million USD, with projections indicating that it will grow to 209.54 million USD by 2032, reflecting a CAGR of 9.70% over the forecast period. The expansion of the robotics market is primarily driven by the growing demand for automation in construction, labor shortages in developed countries, and the increasing need for faster, more cost-efficient, and precise bricklaying solutions. Furthermore, advances in robotics and artificial intelligence technologies have improved the efficiency, adaptability, and safety of bricklaying operations, accelerating market growth. Robots increase production efficiency and ensure uniform quality in construction tasks, making them ideal for large-scale construction endeavors. The construction industry is increasingly adopting bricklaying robots as companies aim to optimize their processes and improve the accuracy of bricklaying through automation. The incorporation of robotic systems is revolutionizing traditional masonry methods by increasing speed, minimizing human errors, and reducing long-term labor expenses. The United States leads the bricklaying robot market, holding the largest revenue share of 38% in 2024, due to the widespread use of construction automation and advanced robotics technology. The robust development of infrastructure in the region and labor shortages are key factors driving the adoption of robotic systems to increase productivity and shorten construction timelines.

According to the Market Research Future analysis, the market size for bricklaying robots was estimated to be 1.659 billion USD in 2024. The bricklaying robot industry is projected to grow from 1.915 billion USD in 2025 to 8.015 billion USD by 2035, with a CAGR of 15.39% during the forecast period of 2025–2035 [19]. The bricklaying robot market is currently in a transformation phase, with progress in automation and robotization technology. As construction projects become increasingly complex, the demand for precise and effective robotic bricklaying solutions is increasing. This trend in bricklaying robotics is influenced by the need to increase productivity and reduce labor costs, as traditional methods cannot meet the growing expectations of modern construction industries. The integration of artificial intelligence and machine learning into bricklaying robots has the

potential to improve construction adaptability and performance in various environments. Sustainability construction issues shape the bricklaying robot market, and stakeholders are increasingly focused on minimizing waste and optimizing resource utilization.

According to a global survey conducted by ABB Concern that included 1900 construction companies, large and small, in Europe, the US, and China, almost 91% of respondents anticipate a labor shortage in the next decade, and 44% reported difficulties in hiring for construction roles [20]. Among those surveyed, 42% emphasized the importance of improving health and safety on construction sites, while the same percentage highlighted environmental issues as a significant driver of change in the construction industry. Although currently only a few companies in the construction industry utilize robotics, 81% of these firms plan to adopt or expand their use of robotics and automation over the next ten years. In pilot projects, a 15% improvement in efficiency and a 38% increase in the speed of construction production were observed, while waste was reduced by 30%. These projects involved the automated assembly of walls, floors, and ceilings for affordable multi-story, multi-unit housing, robotic elevator installation, and robotic automation of prefabricated modular home production. Robot welding in the on-site construction of steel reinforcement baskets has improved quality, increased productivity, and improved safety. This approach also reduces costs and the environmental impact associated with transporting large finished reinforcement baskets to construction sites. ABB has contributed to ETH Zurich's research on the application of robotic fabrication for architecture and construction and has played a role in creating the world's first laboratory dedicated to collaborative robotic digital fabrication in architecture [21]. The use of robots by ETH Zurich combined with digital design tools means that new architectural esthetics with innovative shapes and patterns have become possible, including intricate building parts made of wood, concrete, brick, and foam [21]. Collective construction robots (CRCs) focus on multi-robot autonomous physical systems that alter a common environment based on user-defined objectives [22]. CRCs are used in architecture, allowing multiple robots to collaborate in the construction of complex structures to achieve scalability and adaptability [23].

1.2. Survey Studies of Construction Robotization

The scientific literature on construction robotics often uses survey research to identify regional adoption patterns, economic barriers, and stakeholder attitudes. Research typically follows two formats: primary stakeholder surveys (questionnaires sent to professionals) and bibliometric reviews (mapping global output through journal analyses). The survey and review of the literature will fill the gap in identifying the challenges and limitations associated with the implementation of construction robots and the opportunities they offer to the construction industry. To achieve this objective, a systematic review of the literature was conducted using the preferred reporting items for systematic reviews and meta-analysis protocol (PRISMA) [24].

The Construction Automation and Robotics for Sustainability Assessment Method (CARSAM) is a specialized research framework used to evaluate the adoption, technological maturity, and impact of the sustainability of construction automation and robots (CAR) [25]. Unlike general industry surveys, scientific papers using the CARSAM typically combine stakeholder questionnaires with technical performance data to evaluate robots in four dimensions: environmental, social, technological, and economic. The transition from Construction 4.0 (BIM and CDE) to Construction 5.0, which emphasizes human-centricity, sustainability, and green design, introduces a new layer of complexity to human–robot collaboration (HRC) [26]. Construction 5.0 focuses on collaboration between humans and robots to improve well-being and solve social, environmental, economic, and cognitive problems. In [27], the first bibliometric

analysis was performed, comparing data from the literature on Industry 4.0, Construction 4.0, and Industry 5.0.

Surveys on the state of construction robotization, with particular emphasis on bricklaying robots, have been conducted globally. These surveys mainly concern the global construction industry, specialized construction market research, and academic case studies in specific countries.

In [28], the possibility of implementing robotization in public housing construction (PHC) was examined in Hong Kong with funding from the Construction Industry Council (CIC). Structured decision-making tools have been developed to identify the challenges faced by the primary PHC sector in Hong Kong. The survey results offer detailed guidelines that can serve as a resource for making development decisions in the construction sector. Their aim is to promote the exploration of innovative and compatible solutions and the future integration of robotic technologies into the construction industry.

The study in [29] aimed to investigate the challenges associated with the adoption of robotic construction technology in the construction industry in Klang Valley, Malaysia. Research data were collected using a quantitative method involving surveys administered to 180 construction contractors in Kuala Lumpur. Researchers collected 50 valid responses and analyzed the data using the IBM Statistical Package for the Social Sciences (SPSS) 29.0. The survey revealed that the main challenges in implementing construction robotics in Malaysia were the high costs related to upgrading construction and robotic technology.

In [30], the study explored the perspectives of construction contractors on the use of semi-automated masons (SAMs) as an alternative building technique in the South African construction sector. This study used a non-probability objective sampling method for 20 construction companies located in Durban, KwaZulu-Natal. Data were collected through semi-structured telephone interviews with participants from the construction firm, and thematic analysis was performed using NVivo 12 software. The research findings indicate that the construction industry is open to integrating SAMs into its construction tasks; however, they feel that the South African construction sector is not yet ready to embrace these technological advances. The participants highlighted the high unemployment rate in South Africa, the potential for significant job losses among manual laborers, and the substantial expense of robots, all of which represent major hurdles for companies considering the implementation of robotic technology.

In [31], case studies, expert opinions, and the relevant literature were used to identify areas that require the standardization of robotic construction, investigating and evaluating the influence of mobile robots while addressing labor issues, waste minimization, and sustainability goals in large construction projects in India.

In [32], factors that affect construction development projects were analyzed within Saudi Arabia's Vision 2030, based on a survey of 1076 engineers in the Saudi construction sector. Pearson's chi-square test was used to illustrate the relationships between demographics, project attributes, and the factors that influence costs. The results indicate several elements that influence expenses, including inadequate project management, incorrect cost assessment, and design flaws. This study shows how engineers' experience and education influence their views on cost factors. The surveys revealed that improved project management techniques, better technical training, and the adoption of digital technologies such as Construction 4.0 are essential for reducing cost-related risks. This study provides valuable information to construction professionals and policymakers to improve cost management within the construction sector in Saudi Arabia.

1.3. Review of Construction Robotics

Construction robotics offers various challenges and opportunities to promote sustainable construction in key tasks [33–37].

1. Improved efficiency and productivity: Construction robots can perform tasks more accurately than manual human work, producing higher-quality results with fewer mistakes. This increased efficiency can lead to reduced waste and more sustainable resource use.
2. Waste reduction: Robotics can contribute to waste reduction in construction investments.
3. Optimization and simulation: Robotics and other digital technologies enable better optimization, simulation, and decision-making in construction technologies, which can lead to sustainable outcomes.
4. Real-time monitoring and control: Robotic and digital technologies have the potential to revolutionize the sustainability of construction through real-time monitoring, optimization, and green design.
5. Enhanced safety: Robotics can be used to identify hazards and safe work procedures, potentially reducing accidents and improving overall site safety.

The integration of robotics and automation in sustainable construction has become a groundbreaking element that revolutionizes the way building processes are carried out. The construction industry requires robotization to address the challenges of urbanization, climate change, and sustainability. Robots have a significant impact on improving productivity, efficiency, and adaptability in the construction industry. The review in [38] discusses research studies that aim to improve automation in the construction industry and proposes advances in construction robots. Robots in the construction industry can perform a wide range of tasks, such as bricklaying [39], plastering [40], painting [41], printing [42], demolition [43], welding [44], material handling [45], excavation [46], producing building components and modular homes [47], and creating unique architectural structures [48]. Robotization in the construction industry can be used to create more economical buildings, improve quality, and reduce waste in sustainable environments [49–51].

Several types of industrial robots are used in construction, including SCARA robots for prefabrication and modular construction, articulated robots for a wide range of tasks such as welding, painting, plastering, bricklaying, and assembly, cylindrical robots for tasks requiring vertical and rotational movement in machine operation and packaging, Cartesian robots for 3D printing and material handling, Delta parallel robots for pick-and-place, sorting, and packaging, and collaborative robots (cobots) for handling lightweight materials and performing assembly and support tasks. Robots with varying degrees of autonomy can be used in construction: semi-autonomous robots, which require initial human involvement and can independently perform construction tasks; autonomous robots, which require no human assistance; and remotely controlled robots, whose control involves some degree of interaction with teleoperators. Mobile robots are used in most on-site construction [52,53], whereas stationary robots are more suitable for in situ prefabrication factories [54,55]. Mobile robots are effective when flexibility at work is a priority, whereas stationary robots excel when productivity at work is a priority. The use of mobile robots in on-site construction presents unique challenges, including state estimation, environmental perception, motion planning, and motion control. Wheeled robots are ideal for navigating flat and level terrains when tracked undercarriage robots can overcome various obstacles.

1.4. Review of Bricklaying Robots

Bricklaying robots with the kinematics of industrial robots are used to perform one of the most time-consuming and physically demanding tasks in construction: wall bricklaying [56]. Bricklayer robots help bricklayers perform repetitive and physically de-

manding masonry tasks, whereas construction workers can perform more complex and specialized tasks [57,58]. In semi-automated bricklaying systems, robots lay bricks, whereas workers perform tasks such as applying mortar and aligning bricks. In automated bricklaying systems, robots equipped with sensors and software perform the entire bricklaying process, including picking bricks, applying mortar, and bricklaying precisely according to design specifications.

An analysis of bricklaying robots indicates that most of their applications are in architectural construction, placing dry blocks (without mortar) in open areas [59]. Bricklaying walls inside buildings with a robot is a challenging task because it requires the placement of blocks with applied mortar in tight spaces, such as the space between columns, along side walls, and on walls with openings for doors or windows. Bricklaying robots are limited when laying bricks in the ceiling and side courses, recesses, lintels, and corners.

The most well-known applications of robots for bricklaying are discussed.

At the Budapest University of Technology and Economics (Hungary), a study was conducted to evaluate the automatic bricklaying times of straight walls in two ways: by optimizing traditional and unconventional bricklaying methods [60]. In this study, a small 4-axis Dobot Magician MG400 educational robot was used, which moved on a rail and was equipped with an air gripper. The bricks were picked from a pallet and placed on the wall without mortar in various patterns. The Dobot Studio application was used to program simple robot tasks, and the Python programming language was used for more complex tasks. Various factors influencing the bricklaying process were investigated to obtain optimal solutions.

The construction materials company Wienerberger A.G. from Austria presented a heavy bricklaying robot, the WLTR, at the GEMO a.s. construction site in Šumperk, Czech Republic, which was developed through a collaboration with the Czech startup KM Robotics [61]. The 6-axis articulated serial robot WLTR was used to build long, straight walls with a height of 2.75 m at a capacity of up to 10 m^2 per hour, weighs 2.5 tons, moves elements up to 120 kg, and operates at a pace equivalent to that of a five-person team. The operator uses a tablet to position the robot on-site and locate the bricklaying site on the wall. The robot independently picks a brick from a pallet, applies mortar, and places it in a specified location. Special robot-ready (RR) bricks are used for bricklaying, similar to standard bricks, but with special gripping grooves. The robot cannot complete the first row of wall foundations or corners. In 2025, the first kindergarten construction project in outdoor technology using the WLTR bricklaying robot was started in Koronowo, Poland [62]. A team of several people, supported by two robots, worked on the construction site to construct approximately 600 m^2 of structural walls within seven days. In comparison, using traditional methods, the same stage would have required a three-person team for at least two weeks to complete. The WLTR robots performed the most physically demanding tasks, such as moving heavy blocks, applying foam adhesive, and precisely aligning elements on the wall. This allowed the bricklayers to focus on key construction details, and the work was completed more quickly, safely, and with complete consistency.

Ballast Nedam (a Dutch construction and engineering company) developed and built a bricklaying robot in cooperation with a start-up, which was implemented as part of the Tuinbuurt Vrijlandt low-energy construction project in Rotterdam [63]. The masonry robot supports sustainable construction goals by preventing raw material waste and reducing stone waste by up to 70%. Mortar is precisely dosed on bricks, using 455 g of mortar per brick, compared to 1000 g per brick by a traditional bricklayer. Ballast Nedam invests in innovative technologies and transforms construction sites into modern production facilities by implementing new robotic technologies.

A construction robotics company from Pocklington, Yorkshire, UK has developed an automated bricklaying robot (ABLR) guided on rails, designed for exterior bricklaying

using any type of brick and mortar [64]. The ABLR uses a unique portal frame (gantry) kinematic system and travels horizontally along the tracks on the ground around the house and along the length of the walls. The ABLR frame is telescopic and can be built up to two stories high without requiring additional scaffolding. The ABLR is designed to lay inside and outside blocks or bricks and apply mortar in a single process using standard sand/cement mortar. Because the ABLR moves on a precise 360-degree rail system, it can build corners and leave gaps for windows and doors according to digital CAD plans. The ABLR is equipped with advanced control software, including a BIM interface. Automated bricklaying requires human intervention to load bricks and mortar, remove excess mortar, and finish lintels and corners. The ABLR has been integrated with Material Requirements Planning (MRP) systems and QR code-based material flow control, minimizing waste on-site in line with sustainable building practices. ABLR provides greater flexibility in bricklaying construction by varying the shapes, bonding patterns, and textures of bricks, ensuring high-quality masonry, which is crucial for customizing the homes.

The most well-known worldwide is the Semi-Automated Mason SAM100, designed by the New York company Construction Robotics (CR) [65]. The SAM100's principle of operation is based on HRC, which automates the heavy and repetitive tasks of bricklaying but still relies on humans for material supply, quality control, and finishing. The bricklaying operation begins with the manual loading of bricks onto a conveyor belt, and mortar is fed into a specialized on-board pump. An operator uses a tablet interface to program the SAM100 with the specific dimensions of the wall, where the openings (windows/doors) are located, and what the brick pattern (bond) should be. The SAM100 is mounted on a specialized track system integrated with professional scaffolding, which moves along the wall and is elevated as the wall grows taller. The SAM100 effector is equipped with a laser, which allows it to be oriented relative to the wall during bricklaying and helps determine the position of the brick for the next cycle. The SAM100 is suitable for masonry work on the exterior walls of large buildings, such as commercial pavilions and industrial halls. The SAM100 can lay between 2000 and 3000 bricks per day at a maximum rate of approximately 300–400 bricks per hour, which is approximately five to six times faster than a single human mason.

Hadrian X, developed by Fastbrick Robotics (FBR) in Australia (Perth, Australia), is an advanced autonomous truck-mounted bricklaying robot that can brick entire building structures from a crane boom [66]. The Hadrian X can be mounted on a 25-ton truck chassis and driven to a construction site, where it can be easily deployed and operated from a street or single driveway spot. The rear of the truck is designed to load brick pallets directly onto Hadrian X, and the bricks are transported by a specialized internal shuttle from the truck to the placement head. Hadrian X includes an internal saw module that can cut bricks to any size required for window/door openings or gable ends that minimize material waste. The most visible structural component is the massive robotic boom, which features a 32 m telescopic arm. This long reach allows the robot to build a standard single- or two-story home, including internal and external walls, without moving the truck to a new location. At the end of the long boom, a specialized robotic head (end effector) is placed. The gripper picks up the block from the internal shuttle, applies the adhesive, and places it with millimeter precision. Hadrian X uses a proprietary construction adhesive that cures much faster (in minutes), allowing walls to be built quickly without waiting for the wet mortar to set. Due to wind, vibration, and mechanical movement, long booms are strongly swayed, making bricklaying precision impossible. Hadrian X is optimized for speed using large-scale blocks. The Next-Gen Hadrian X can lay up to 300–500 blocks per hour, which is equivalent to laying approximately 1000–3000 standard bricks per hour. Hadrian X can complete the structural walls of a standard suburban house in 1 to 3 days, a process that typically takes a manual crew 1 to 3 weeks.

The Dutch startup Monumental developed a robotic bricklaying system that can be classified as an "additive construction" [67]. Additive construction technology provides an opportunity to reduce labor, material, and transportation costs by equipping robots with mortar extruders to lay bricks.

A construction project in outdoor conditions with the incorporation of a bricklaying robot generally focuses on improving speed, precision, safety, and cost efficiency compared with manual masonry. Bricklaying robots suitable for outdoor construction include Hadrian X, which is one of the most advanced fully autonomous outdoor masonry systems; WLTR for a high-precision outdoor robot for industrial and residential construction; SAM100 for outdoor work with human masons; not fully autonomous but highly effective; Ballast Nedam for bricklaying robots in outdoor projects. Outdoor construction projects can benefit from faster, higher-precision, and better quality buildings. Lower material waste, highly optimized mortar/adhesive dosing, improved safety, reduced work at height, limited repetitive strain, and heavy lifting can also be achieved by workers.

Unlike unique systems and robots, such as Hadrian X or SAM100, which are proprietary designs, many construction companies use industrial robots from the big four, such as ABB [68,69], Kuka [70,71], Fanuc [72,73], and Yaskawa [74], for bricklaying, assembly, prefabrication, and material production, adding their own software, mobile platform, grippers, and other tools to turn them into robotic bricklaying or construction systems. Many innovative projects focusing on the robotization of construction are being developed in cooperation with industrial partners, such as robot contractors, manufacturers of building materials, prefabricated factories, and construction investors, supported by research and development units, scientific institutes, and technical universities. By 2026, vendor consolidation and strategic acquisitions are expected to increase significantly. Larger global firms, such as ABB, are likely to acquire innovative construction startups to expand their portfolios.

This case study presents an example of the implementation of innovation in bricklaying robotization in Poland using a mobile RBS (in Polish ZSM—Zrobotyzowony System Murarski), which was created as a result of a research and development (R&D) project led by the research leader of Kielce University of Technology with the global construction partner STRABAG Poland Ltd. (Pruszków, Poland) [75]. The first original Polish mobile RBS was created from scratch through design, simulation, manufacturing, testing, evaluation, and commercialization in laboratory settings, demonstrations on construction sites, and commissioned bricklaying walls on-site in residential construction. The mobile RBS is designed for bricklaying applications inside public, residential, and industrial buildings, primarily to build partition walls and walls with windows and/or doors.

The Materials and Methods section contains details of the design of the RBS solutions. The Results section presents simulated, virtual, and real robotic bricklaying processes. The Discussion section summarizes the results of bricklaying using the RBS and the factors that influence the robotic bricklaying process. In this study, the term bricklaying is used, which specifically refers to laying bricks, whereas the term masonry is a broader term encompassing stone, marble, granite, and block work.

2. Materials and Methods

2.1. RBS Design Solutions

For bricklaying processes, the mobile RBS uses the ABB IRB 4600 industrial robot, ABB, Västerås, Sweden, with a hydraulic gripper, which is mounted on a support frame embedded in a Hinowa tracked undercarriage, Nogara, Italy, with a hydraulic drive. Front and rear hydraulic lifting and leveling units, a brick warehouse with a brick feeder, a hydraulic and electric power control unit, and a robot control cabinet were installed on the

robot support frame. Figure 1 shows a three-dimensional CAD model of the mobile RBS design with an industrial robot and its basic components [76].

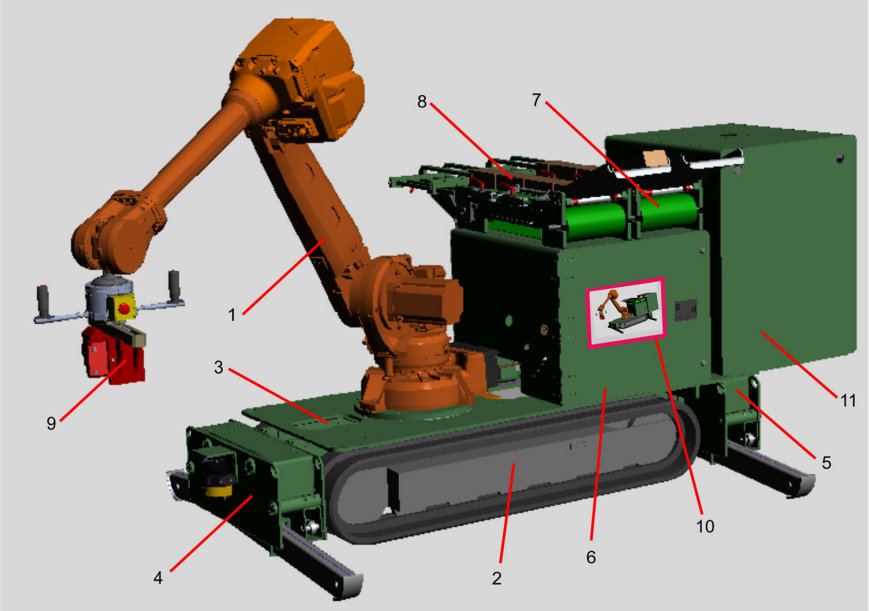


Figure 1. Three-dimensional CAD model of the mobile RBS design: 1—ABB IRB 4600 industrial robot, 2—Hinowa tracked undercarriage with hydraulic drive, 3—robot support frame, 4—front hydraulic lifting and leveling unit, 5—rear hydraulic lifting and leveling unit, 6—hydraulic and electric power control unit, 7—brick warehouse, 8—brick feeder, 9—hydraulic gripper, 10—HMI touch control panel, and 11—robot control cabinet.

To select a suitable industrial robot for bricklaying, various types of industrial robots from different companies were evaluated in this study. Due to the unique tasks of construction robots, the main factors that affect the selection of industrial robots are their parameters, such as workspace, number of degrees of freedom (DOF), specific weight, payload capacity, moving speed, and programming and control system. Among various industrial robots, the 6-DOF industrial robot type ABB IRB 4600-40/2.55 from ABB meets the RBS requirements more effectively [77]. The ABB IRB 4600 is a compact high-speed industrial robot weighing 450 kg, with payloads ranging from 20 to 60 kg, and a high positional repeatability of 0.05 to 0.06 mm. Figure 2 shows a view of the RBS with an ABB IRB 4600 industrial robot and its components.

Considering the dimensions of the rooms, corridors, and door openings used in apartment buildings, the external dimensions of the RBS were limited to a width of 890 mm, height of 1628 mm, and length of 3235 mm. The external dimensions of the RBS are shown in Figure 3.

The mobile RBS allows the bricklaying of walls in large workspaces but is limited by the workspace of the arm robot. The range of the ABB IRB 4600 robot arm in the base position, required by the conditions of the construction site, is shown in Figure 4.

In the RBS, an ABB IRC5 controller was used to manage the most recent ABB IRB 4600 robot, which provides flexibility, safety, modularity, application interface, and PC tool support. The IRC5 controller optimizes the robot performance for the shortest possible physical cycle time (QuickMove) and precise path accuracy (TrueMove). The IRC5 controller operates in both online and offline modes. The offline mode cooperates with RobotStudio to provide a perfect digital copy of the robot system along with strong programming and simulation features. In the online mode, it cooperates with FlexPendant TPU (Teach Pendant Unit), which uses the RAPID programming language and has a color touch screen and a 3D

joystick. RAPID is easy to use and is a universal language that supports structured programs useful in bricklaying processes. Figure 5 shows the ABB FlexPendant handheld controller unit [78]. A portable ABB FlexPendant touch panel with the software tools of the Flex-Pendant SDK can perform various tasks, such as running programs, controlling the robot, and making changes to robot programs.

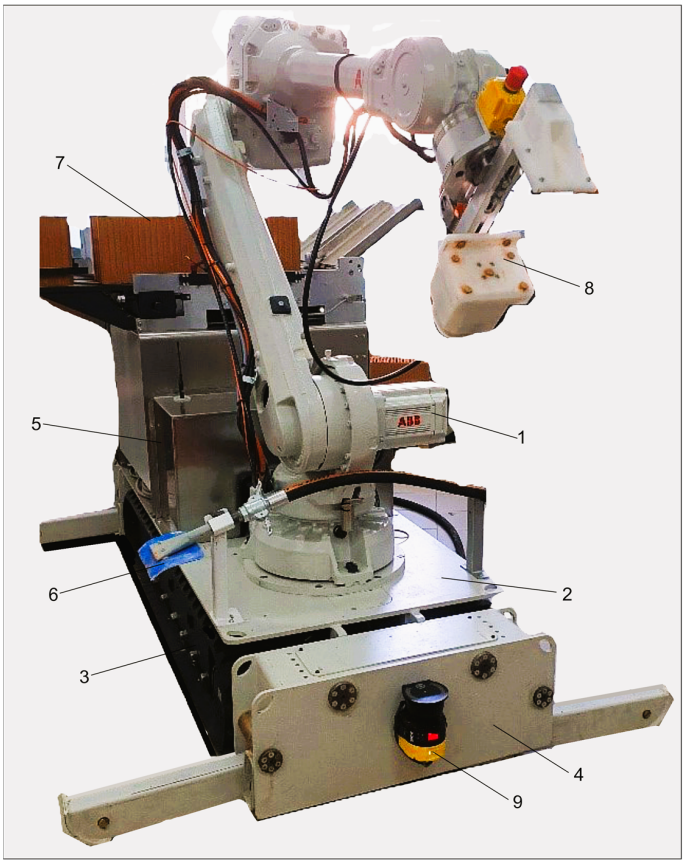


Figure 2. View of RBS: 1—ABB IRB 4600, 2—support frame of robot, 3—Hinowa tracked undercarriage, 4—front hydraulic lifting leveling module, 5—hydraulic power and control module, 6—mortar applicator, 7—brick warehouse, 8—hydraulic robot gripper, and 9—safety laser scanner.

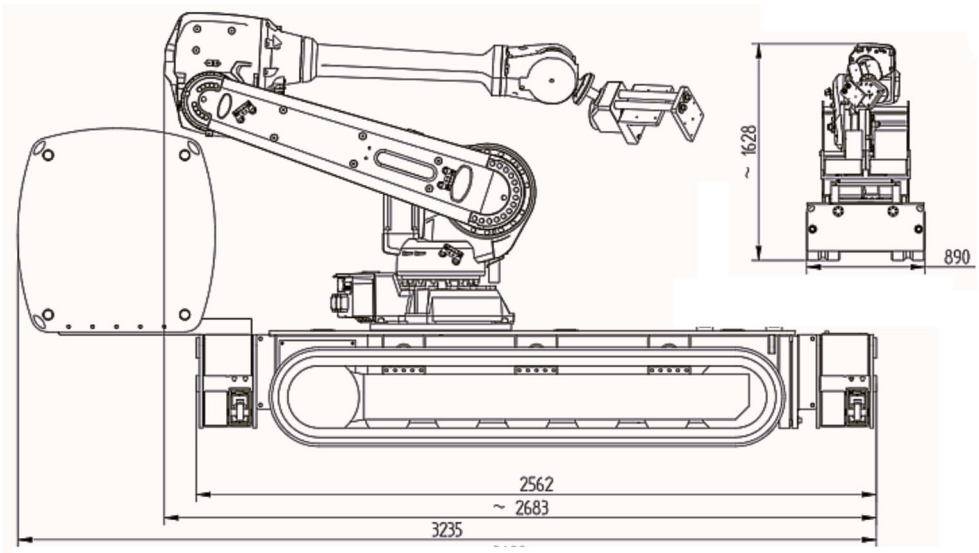


Figure 3. The external dimensions of the RBS.

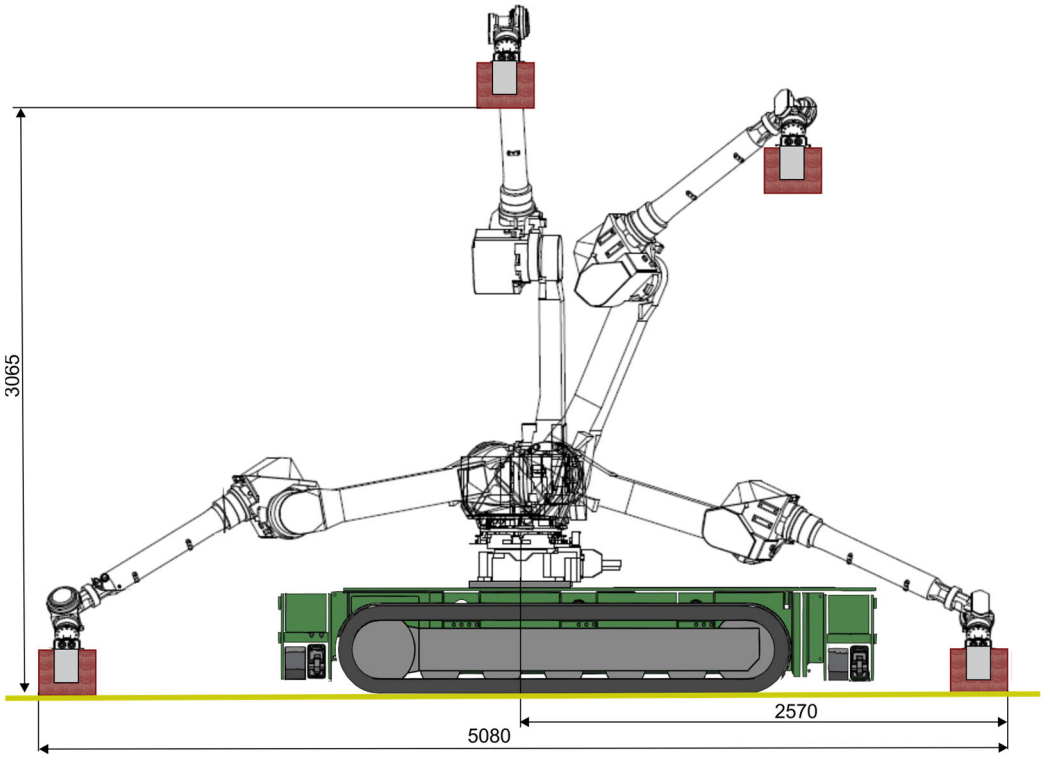


Figure 4. Workspace of an ABB IRB 4600 robot arm in its base position.



Figure 5. ABB FlexPendant handheld controller unit.

The IRC5 controller cooperated with the Siemens Simatic Human Machine Interface (HMI), Karlsruhe, Germany, operator panel built on the Siemens Simatic S7-1500 programmable controller (Siemens, Tokyo, Japan), which was designed using the WinCC Advanced V16 software. The HMI operator system uses the Profinet communication network to ensure the proper functioning and monitoring of different RBS units and modules [79]. Once the control system is activated, the HMI panel displays the start screen, which displays the menus of many function screens, as shown in Figure 6.

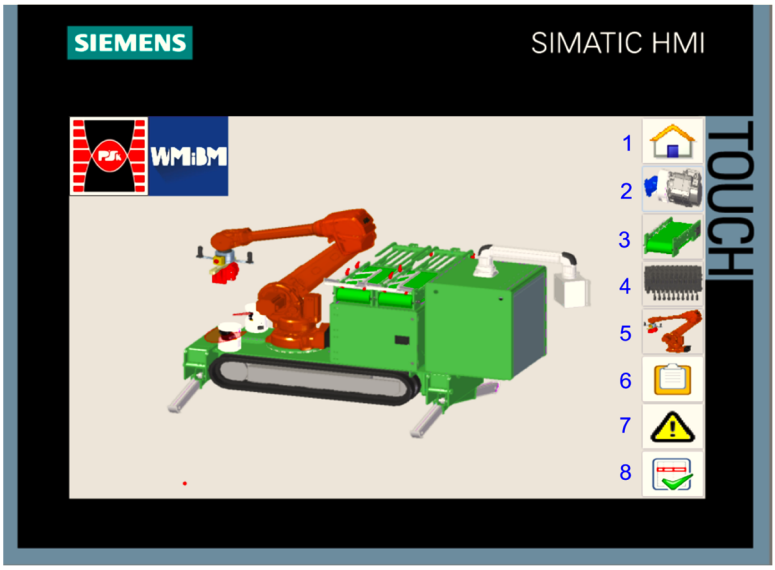


Figure 6. HMI panel start screen: 1—home screen, 2—hydraulic power supply screen, 3—construction materials feeder screen, 4—undercarriage track drive screen, 5—robot screen, 6—technology process procedure screen, 7—failure screen, 8—failure reset button.

A Hinowa PT20GL tracked undercarriage with rubber tracks was used to move the mobile RBS, and the built-in version, patented as an industrial design [80,81], is shown in Figure 7. A functional safety analysis was performed for the hydraulic drive control system of the Hinowa tracked undercarriage [82] according to the ISO 13849-1 standard [83]. The performance level (PL) of the safety function was determined using the SISTEMA 3.0.4 software tools developed by the Institute for Occupational Safety and Health of the German Social Accident Insurance [84].

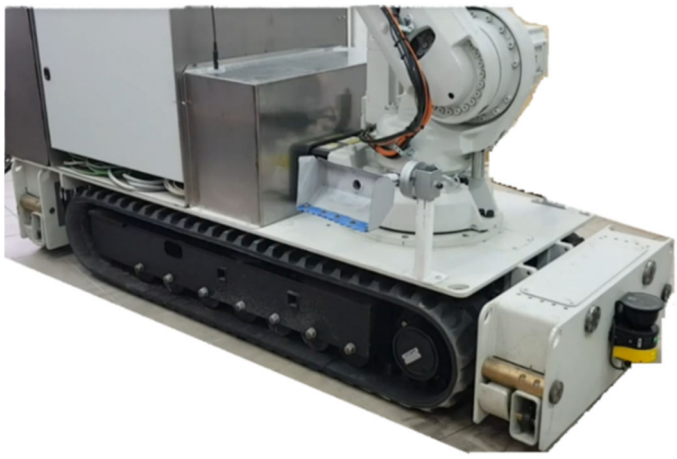


Figure 7. View of the Hinowa-tracked undercarriage build-up.

The hydraulic lifting and leveling unit with two cross-adjustable support legs is shown in Figure 8. After leveling the RBS, the support legs were mechanically locked, which ensured an accurate, durable, solid, and stable position of the ABB IRB 4600 robot at the bricklaying site.

The leveling of the RBS is justified because the robot frequently and heavily loads the masonry blocks. When laying heavy bricks, the robot generates variable dynamic shock loads that are transferred to the hydraulic actuators of the lifting and level modules. Excessive vibration of the mechanical and hydraulic parts occurs due to dynamic shock loads, leading to inaccurate control of the bricklaying robot paths. In addition, hydraulic actuators produce pressure variations and sudden pressure surges, which are known as

water hammers. To prevent these undesirable occurrences in hydraulic systems, a hydraulic shock damper (HSD) is used [85,86]. The use of an HSD in RBSs is vital for ensuring the high quality of bricklaying tasks performed by an automated robot. The accuracy of the robot trajectory path depends on the dynamic loads generated during the movement of the robot arm. The dynamic shock load of the hydraulic actuators depends on the angle and mass load of the robot's movable arms, which are marked on the robot shown in Figure 9.

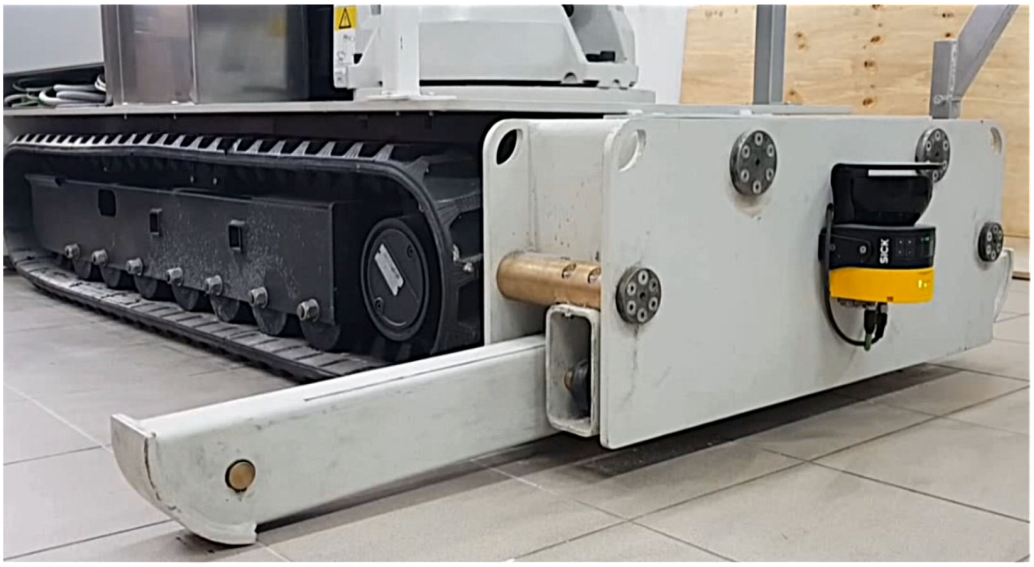


Figure 8. View of the front hydraulic lifting leveling unit.

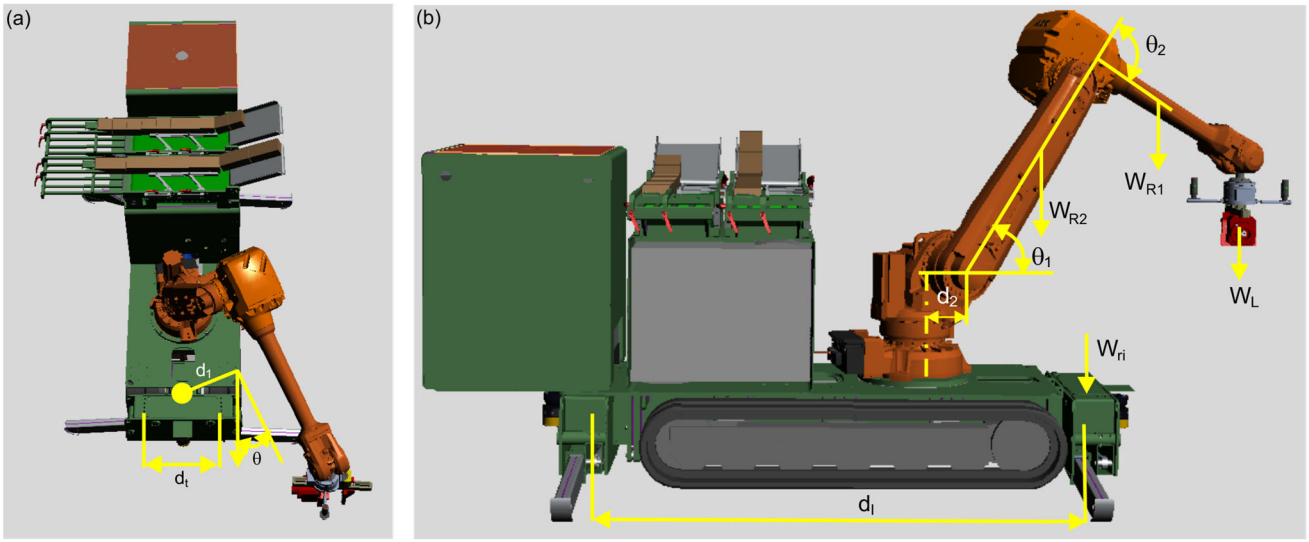


Figure 9. Marking of the mass loads on the bricklaying robot: (**a**) top view of the robot, (**b**) side view of the robot: *Wri* is the weight load of the *i*-th cylinder, α is the angle of vertical deviation of the lifting cylinder, W_R is the weight of the two-link robot arm, $W_R = W_{R1} + W_{R2}$, W_{R1} is the weight of the first link of a robot, W_{R1} is the weight of the second link of a robot, M_L is the weights of the lifted load (griper, brick), θ is the horizontal swing angles of the robot arm, θ_1 and θ_2 are the vertical swing angles of the robot forearm and arm, d_t is the distance between hydraulic actuators in the transverse direction, d_l is the distance between hydraulic actuators in the longitudinal direction, and d_1 and d_2 are the lengths of the links.

For RBSs, a special adjustable industrial robot hydraulic gripper was developed to grip bricks of various sizes, such as bricks, hollow bricks, ceramic blocks, gas concrete blocks, and cellular concrete [79]. When bricks are stacked on a wall, impulsive forces

and moments are generated, which are transferred to the gripper and then to the robot's compliant mechanism, affecting the accuracy of bricklaying. To address this, patented compliance devices [87], that is, a mechanism that provides flexibility, allowing the robot to compensate for misalignment, part tolerances, and positioning errors during bricklaying tasks, such as precise and collision-free brick placement and pressing into the mortar, have been developed. Figure 10 shows the robotic hydraulic gripper and CAD model of the compliant mechanism.

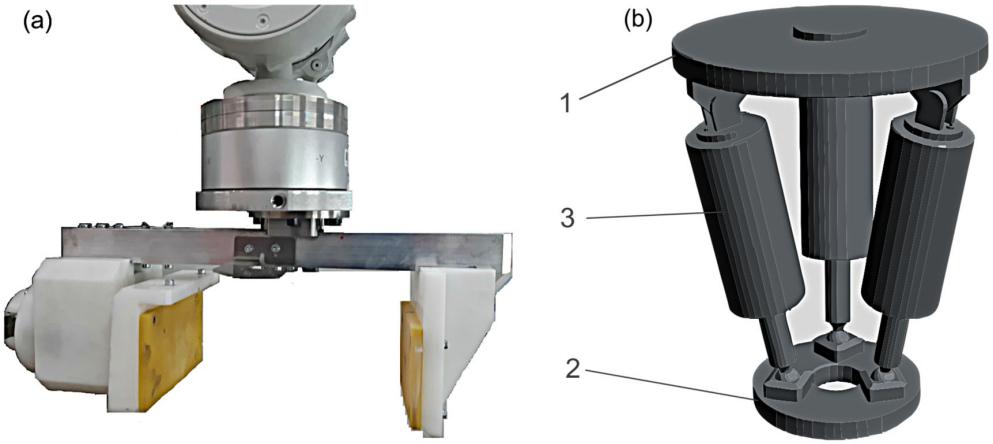


Figure 10. Robotic gripping: (**a**) view of the hydraulic gripper, and (**b**) CAD model of compliance devices: 1—fixed base mounted on the robot wrist; 2—movable platform to mount the robot gripper; and 3—three flexible pneumatic actuators with bellows.

2.2. Simulated Robotic Bricklaying

Robot bricklaying simulators enable the virtual programming of robots that use digital representations of environments and other objects based on their physical models. Planning the trajectory of a bricklaying robot involves determining a time series of subsequent movements of the robot gripper from the starting configuration to the goal configuration to achieve the task of picking a brick from the feeder and placing it in the appropriate layer on the wall. The robot trajectory must respect the given constraints, such as the range of the robot arm and its kinematic parameters, which should be within specified limits. The robot control system selects an optimal trajectory to achieve a specific goal. Minimizing the trajectory execution time is the most common optimization objective in robotics.

RobotStudio is an ABB software package that enables us to simulate, program, and communicate with the ABB IRB 4600 industrial robot [88]. RobotStudio has a built-in integrated development environment (IDE) to edit the code written in the RAPID language and test the kinematics of the ABB IRB 1600 robot offline in the built-in simulator [89]. After testing in the RobotStudio simulator, the RAPID program was transferred to the real robot controller. Figure 11 shows the screen of the RobotStudio simulator with the position program of the ABB IRB 4600 robot.

Simulated online robot programming in RobotStudio involves defining the physical bricklaying site and creating the targets and paths required by the robot to perform the bricklaying tasks [90]. Path creation is a crucial element in robot simulation programming in RobotStudio software. Paths (or trajectories) are sequences of movement instructions used to guide the robot towards a set of targets. The targets are defined and stored as a set of coordinates relative to a coordinate system called the WorkObject. RobotStudio utilizes virtual controllers for the execution of robot programs, which can manipulate virtual robots to test and assess their performance to achieve the desired objectives. Collision detection verified whether a robot or tool encountered obstacles or additional objects near them. The

virtual controller operates using the same software as the RAPID program controller. It performs calculations for robot movements and manages the input/output signals.

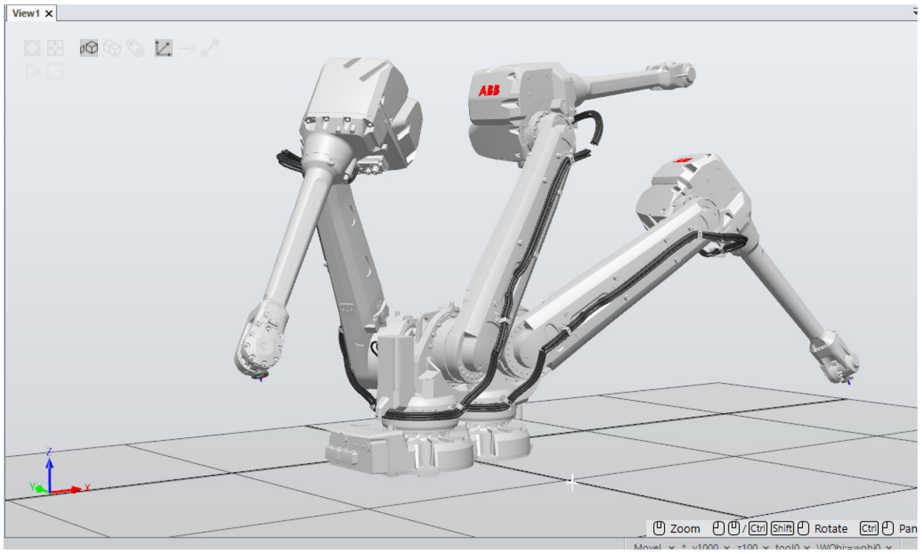


Figure 11. Screen of a RobotStudio simulator with position programming of the ABB IRB 4600 robot.

Figure 12 shows the visualization of various bricklaying processes using the ABB IRB 4600 industrial robot in RobotStudio, with the tool center point (TCP) path of the robot gripper [91].

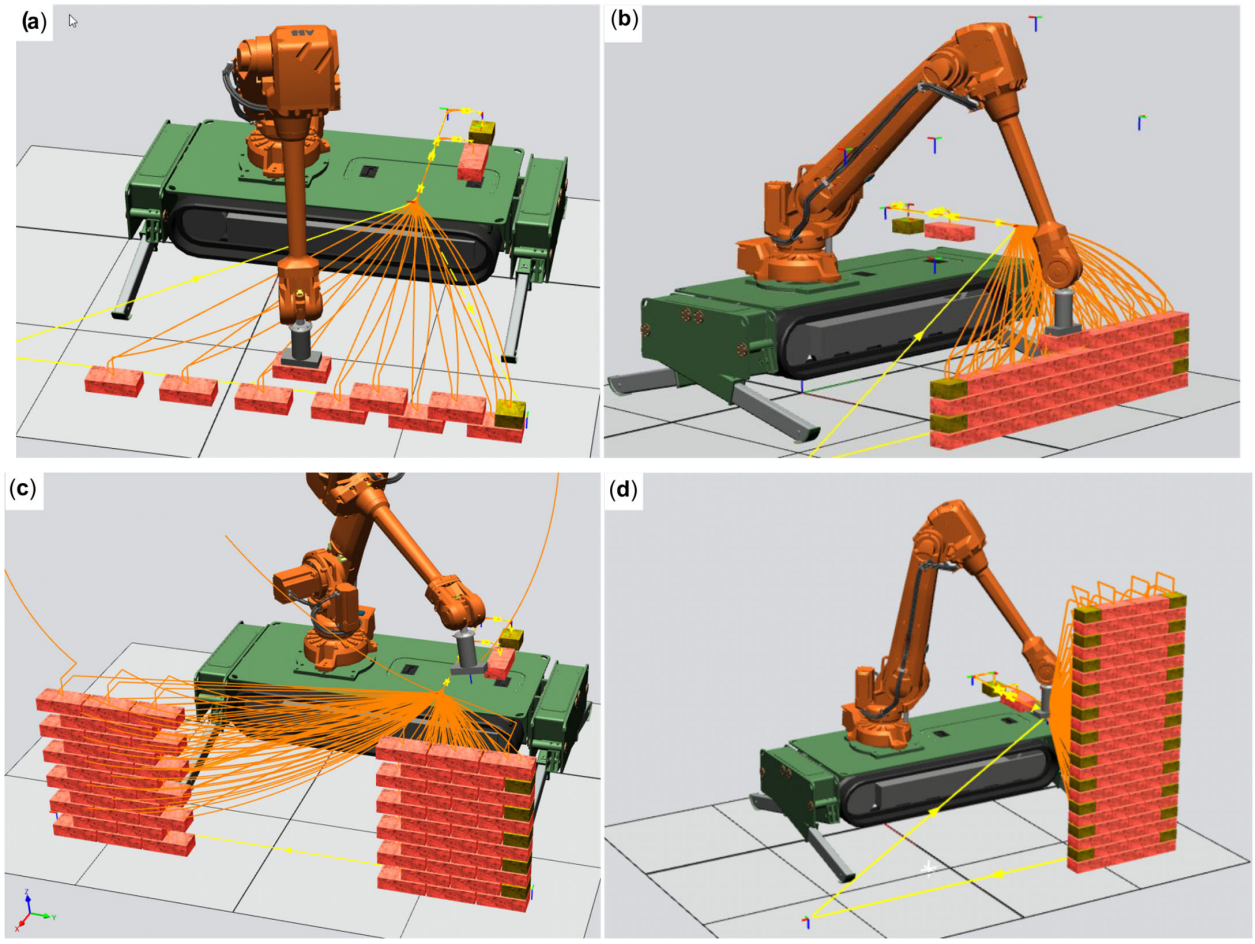


Figure 12. Visualization of various bricklaying processes using the ABB IRB 4600 industrial robot in RobotStudio: (**a**) any bricklaying, (**b**) horizontal wall, (**c**) hole in a wall, and (**d**) vertical wall.

2.3. Digital Environment for Robotic Bricklaying

The integration of BIM and robotics means a symbiosis between the digital system and robotics capabilities; it may involve information on geometric description and location and bricklaying scheduling, its process, and stored metadata that sequentially define objects and areas of the environment [92,93]. The BIM interface enables a two-way connection between BIM objects and the robotic system. Robotic bricklaying becomes more effective and accurate when combined with BIM and digital planning using real-time data and automation-ready geometry. The integration of BIM and robots improves speed, quality, cost control, and workflow reliability at construction sites. Table 1 shows the impact of BIM on robotic bricklaying for specific factors.

Table 1. Impact of BIM on robotic bricklaying.

Factor	Impact
Speed	Faster execution, continuous operation, and direct BIM-to-robot workflows are possible. BIM-to-robot workflows streamline the translation of architectural plans into robotic tasks, improving overall construction speed.
Precision and quality	BIM provides detailed geometric and material data that robots can follow with millimeter precision. BIM supports improved visualization and conflict control, preventing errors, and reducing the need for rework. Robotic systems use BIM as a reference model, whereas measurement systems (laser, vision) check each brick placement. Continuous evaluation of brick alignment, mortar thickness, and structural integrity results in superior uniformity and fewer inconsistencies.
Cost	Robot bricklaying integrated with BIM reduces waste, lowers labor costs, and improves planning accuracy. Reduced rework and waste because robots integrated with BIM place bricks with greater accuracy. Construction projects experience fewer errors, yielding lower material waste and reduced corrective labor requirements. BIM reduces costs by cutting waste, preventing errors, improving planning accuracy, and minimizing reliance on manual labor.
Accuracy and productivity	BIM increases robotic bricklaying productivity by enabling precise automated planning and efficient uninterrupted execution.
Adaptability	Real-time data integration between BIM and robotic systems enables immediate on-site adjustments (e.g., uneven surfaces and shifting tolerances). Robotic bricklaying systems linked to BIM can enable real-time adaptive construction, which accelerates project progress.
Predictability	Robots and BIM integration support predictive modeling and better decision-making in the early stages, reducing cost overruns and errors. High-speed, high-precision robotic masonry improves predictability and reduces overall operational costs. Predictability enables robots to better handle irregular materials for the detection and handling of non-uniform bricks or complex geometries.

Architects and construction designers use various BIM-related programs such as Autodesk Revit [94]. This is an established BIM design software that enables users to create, edit, and view building models in a three-dimensional environment. Autodesk Revit includes features such as 3D design mode, library management, company settings, and custom label design. The benefits of Autodesk Revit for virtual building design include collaboration with other design applications, such as Dalux and ProDesign. Dalux is a cloud-based application that can be used as BIM to manage construction projects [95]. Dalux is known for its functionalities, such as service coordination, user-friendliness, cloud-based, and real-time communication. Autodesk Revit models automatically update any design changes made,

ensuring that design and documentation are coordinated and more reliable. Figure 13 shows a flowchart of the use of a digital environment for the robotic bricklaying.

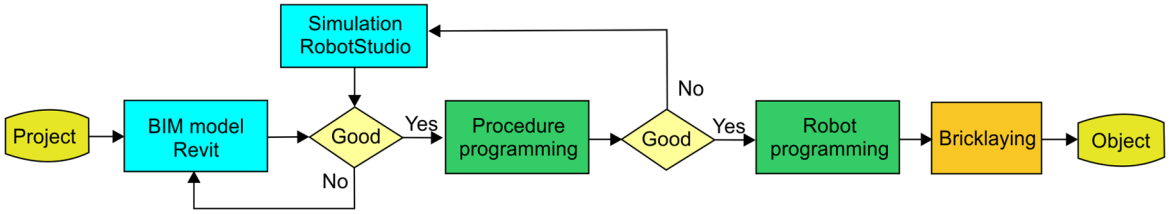


Figure 13. Flowchart of the use of a digital environment for robotic bricklaying.

2.4. Digital Plan of Robotic Bricklaying

A virtual model of the building design was created for the robotic bricklaying project using Autodesk Revit 2025. Figure 14 shows the virtual model of the building design created in Autodesk Revit, including the building under construction, separation of the internal walls, and dimensions of the separated base wall. Building models contain not only physical (geometric) attributes but also retain their functional properties. Individual structural elements, such as walls, can be separated from the building models. Autodesk Revit can be integrated with robotic tools such as ABB RobotStudio. With this tool, a structural model can be transferred from Autodesk Revit to RobotStudio or from RobotStudio to Autodesk Revit. In RobotStudio, there is a geometry export add-on; therefore, the wall geometry can be transferred for robotic bricklaying. The robot simulation model from RobotStudio was transferred to the IRC5 controller of an ABB IRB 4600 robot.

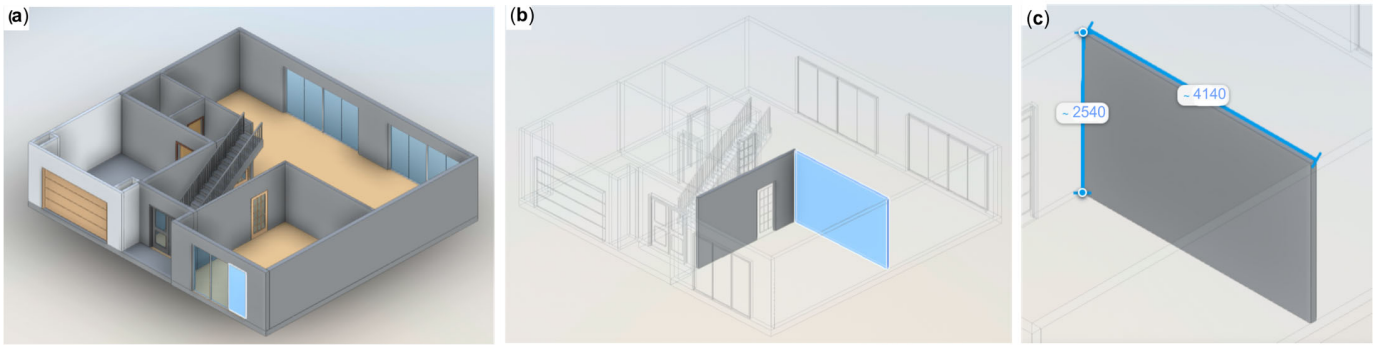


Figure 14. A virtual building design model was created in Autodesk Revit, including: (**a**) building under construction, (**b**) separate interior walls, and (**c**) separate base wall for bricklaying.

The goal was to prepare a cascade: Revit (structural model) → RobotStudio (simulation model) → RAPID (logic and robot trajectories) for constructing an interior wall. We assume that a 2540 × 4150 mm masonry wall can be bricklaying using cell blocks 240 × 240 × 490 mm a stretcher bond with 5 mm horizontal and vertical joints, and that the robot ABB IRB 4600 will automatically pick up, handle, and lay the blocks.

Transferring a model from Autodesk Revit to RobotStudio: Export from Revit: From a single-family home model with internal wall divisions, extract the 2540 × 4150 mm wall of interest as a separate element (for example, the "Wall–Internal" category). Exchange format: The geometric layer of the wall (and reference environment) is exported to a neutral CAD format (for example, SAT/STEP/IGES/STL) or IFC 2×3/4, and then imported to RobotStudio as station objects (Station → Import Geometry). Reference frames: In RobotStudio, a WorkObject wobjWall is defined with its origin in the lower-left corner of the wall; the X axis extends along the length of 4150 mm, the Z axis extends upwards (2540 mm high), and the Y axis is aligned with the wall thickness (240 mm). Robot and

fixture: Add an ABB IRB 4600-40/2.55 (controller IRC5) and gripper model. We set the tooldata to a mass of 7.9 kg and COG [0,0,0].

Dimensional synthesis and block layout plan: The calculations performed by the software for the given dimensions (mm): wall height 2540; layer: 240 + 5 = 245 ⇒ 10 layers are within the limit (10 × 245 = 2450), leaving a 90 mm top gap (to be filled with a ring beam, leveling strip, or countered cuts—outside the scope of this program). Length 4150 mm; longitudinal module 490 + 5 = 495 mm. Number of elements for the entire wall (10 layers): total blocks: 75 pieces. Halves (start of even layers): 5 pieces Final cuts: 10 pieces Example positions (first 10 elements of the entire wall, X axis from the left corner, Z base of a given layer): Layer 1: full at X = 0–490, 495–985, . . ., final cut 3960–4150; Layer 2: start half-block 0–245, then full every 495 mm, etc.

Sequencing algorithm: Global settings: Tooldata definition for the gripper, wobjWall, speed (v100/v200), zone (z10/fine), and I/O signals. Placement grid generator: For layer c = 1.N: z = (c − 1) × (240 + 5) (weld level) with TCP tool offset. Start offset: 0 for odd, 245 + 5 for even (half + welds). Pitch: 490 + 5 (full module). The last element in the layer: cuts—length = remaining space. For each element, pick from the buffer position (brick warehouse) and confirm the grip (DI/DO). Approach over the placeholder: Offs (pBase, x_center, y_set, z_center + h_appr). Place: Move the robot down to the weld level and open the gripper to place the workpiece. Retract: MoveL do z + h_appr. Validations: collision check, OLP → Online, cycle time monitoring, DO check (grab).

RobotStudio → Robot Trajectory Programming goal: The goal was to convert the RobotStudio model and solution (IRB4600 robot station, tool WorkObject, and wall elements) into executable RAPID code with correct tool data, reference frames, and trajectories, which can be uploaded to the Virtual Controller (VC) in RobotStudio and verified using the tool. Subsequently, it was transferred to the physical IRC5 controller (online).

Exporting trajectories from RobotStudio to RAPID (VC → code): In RobotStudio: Open Home → Rapid → Program Data and create a module (e.g., Masonry.mod). The Path & Targets tool is used to generate MoveJ/MoveL movements according to the defined targets (Approach/Place/Retract) and assign them to procedures (e.g., BuildCourse(), BuildWall()), or manually insert points and save them as robtarget. In the Program Editor, the tGripper tool data, wobjWall wobj data, velocities, zones, and main() sequence were all saved. Test it in the Virtual Controller (Play → Simulation). Once the program is running, save the RAPID module (File → Save Module)—this is the "transfer" from RobotStudio to the trajectory program (RAPID), ready for upload to IRC5.

Transfer to the IRC5 controller (online): After verification in VC (collision-free simulation, correct I/O), export the. mod/.prg module. Connect to the IRC5 controller (RobotStudio Online) and create a task or upload the module to an existing controller. Set the same tooldata and wobjWall on the controller (or upload them along with the module). Calibration "on physics": adjust wobjWall (3-point) to the physical wall corner; fine-tune TCP if necessary. Dry-run in T1, then test in T2/Auto—with full safety mode (curtains, scanners, SafeMove). All steps were consistent with the assumed wall and the hardware data.

3. Programming of the RBS

Once the RBS with the ABB IRB 4600 robot is positioned, the masonry process is prepared by setting up the bricklaying procedures. Bricklaying procedures were programmed on HMI touch panel screens and adapted for operation by construction workers trained in their use. The ABB RB 4600 robot can be programmed using an online teaching mode, in which the programmer manually moves the robot arm by pressing/pulling the robot gripper, which is tedious and time-consuming. When the manual or jogging mode is selected, the menu on the ABB Flexpendant panel must be used. All robot tools, including

grippers, must have defined coordinates for the center point (TCP), weight, and center of gravity (COG). These data were recorded in the robot control system and saved on the panel screen to obtain the correct TCP positions. The number of P_i points of the wall coordinates and TCP positions was selected; the default was four, and the maximum was nine. The XYZ TCP coordinates were read for the *Pi* points determined from the wall coordinates. Figure 15 shows the HMI panel screen used to record the P_i points of the wall coordinates and TCP position in the point-to-point (PTP) robot teaching mode.

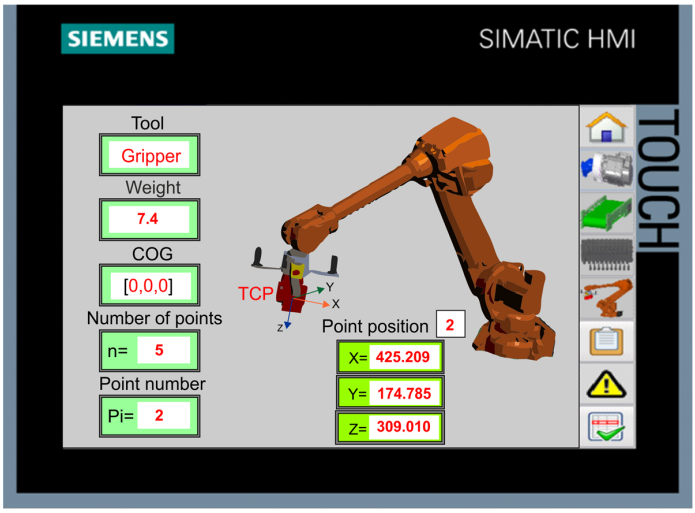


Figure 15. HMI panel screen to record the Pi points of the wall coordinates.

In offline mode, the programmer enters the program code with predetermined trajectory points. Off-line programming enables operators to program complex geometries quickly while utilizing the maximum accuracy and capability of the robot system [96]. Offline programming is supported by laser measurements of wall coordinates. The boundaries of the wall bricklaying were marked with cross-points (CPs) using a cross-line laser (CLL). If the coordinates of the laying point of the current brick were above the CP laser beam, the brick was laid sideways on the wall and pressed with a gripper. However, if the coordinates of the current bricklaying point were below the CP, the brick was placed on the wall from the top and pressed with a gripper. Figure 16 shows the wall use of CLL to determine the dimensions and program the bricklaying process [91,96].

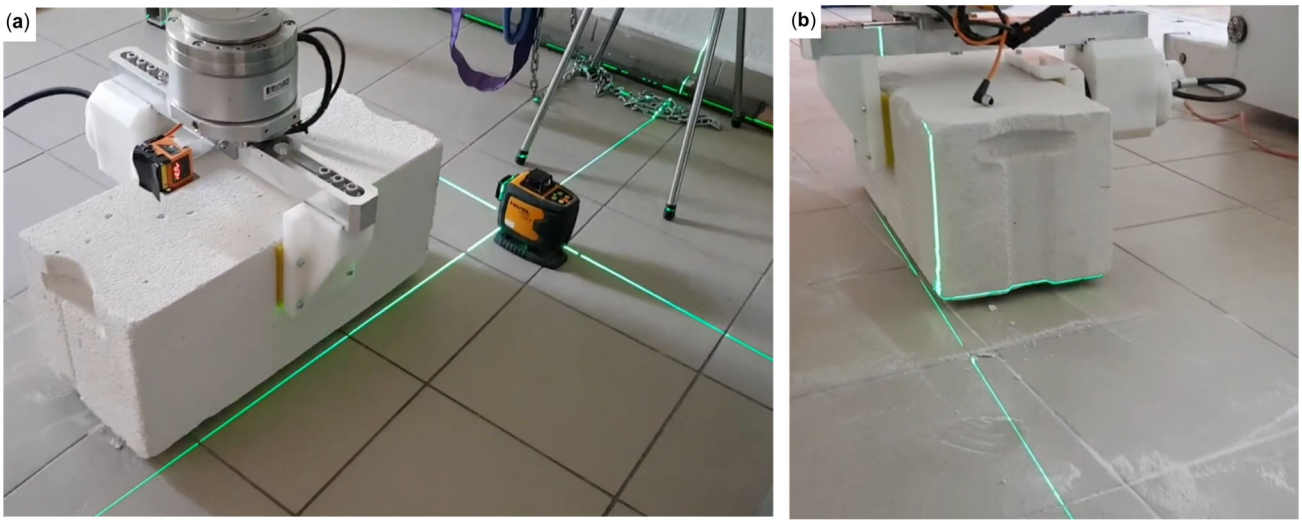


Figure 16. Photos (**a**,**b**) show the use of CLL to determine the dimensions of the wall and program the bricklaying process.

The high-intensity green laser diode (GLD) ensured maximum visibility and detection of the boundary of the brick wall. The CLL has a working range of 30–100 m, 360° rotation, and a self-leveling mode, indicating an out-of-level condition with a range of 4°.

Figure 17 shows the panel screen used to measure the wall parameters with CLL. Laser measurements of the wall length and height, as well as the horizontal angle of the wall, were recorded on the HMI panel screen, and the dimensions of the brick and thickness of the mortar were entered, which were used to program the brickwork procedures.

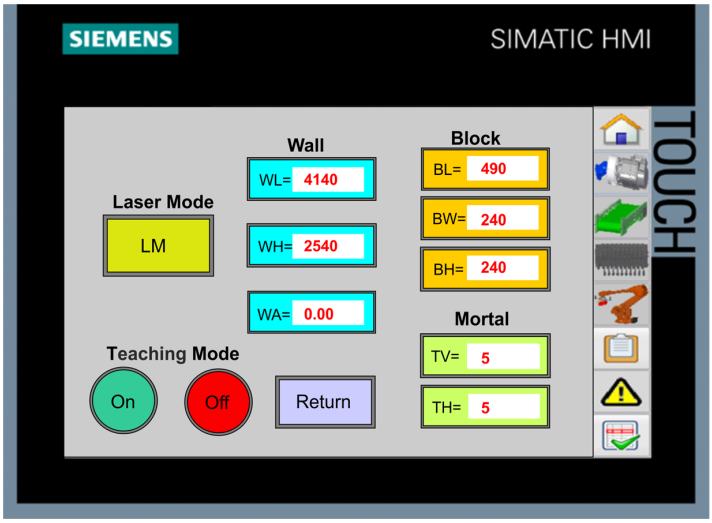


Figure 17. HMI panel screen to measure wall parameters using CLL: LM—button to activate wall measurement, WL—wall length, WH—wall height, WA—horizontal angle of a wall, BL—block length, BW—block width, BH—block height, TV—thickness of the vertical joint mortar, TH—thickness of the horizontal joint mortar, On—button to activate teaching mode, Off—button to deactivate teaching mode, Return—back to the previous screen.

The robot controller uses a laser rangefinder (LRF) to determine the position of the gripper relative to the wall. After the n-th cell block is placed in the wall layer at point[n], the LRF measurement of the distance to the end point of the wall is performed. The angle of rotation around the Z-axis of the cell block and the distance to the end of the wall were read using the instructions of the LRF_Laser procedure. The LRF laser acts as the dataset for the robot's coordinate system, allowing it to transition from the digital mode to the real dimensions of cell blocks and walls with high-level accuracy. The combination of the LRF operation and bricklaying process algorithm allows the robot to self-calibrate in response to any unpredictable changes or deviations created while laying the aerated bricks, allowing the successful construction of a stable wall. Due to the use of the LRF, the robotic bricklaying process is performed efficiently with optimal precision and minimal downtime. Figure 18 shows the use of the LRF when a cell block is staked on a wall [91,96].

Figure 19 shows the HMI panel screen, where the number of layers of blocks (bricks) and half blocks (half bricks) can be selected, and the number of blocks (bricks) in a wall can be calculated. The number of full and half blocks (bricks) in each layer of the wall was calculated using the laser measurement of the wall dimensions, considering their dimensions. During bricklaying, full and half blocks (bricks) are selected in the order they will be laid on the wall.

Robotic bricklaying is performed cyclically with a fixed or variable robot arm trajectory. The fixed robot trajectory was between the brick warehouse and mortar applicator. The variable trajectory of the robot runs between the mortar applicator and the laying point on the wall and from the laying point to the brick feeder. Based on the robot trajectories of the

programs, appropriate procedures were implemented for the bricklaying process, which can be called on the HMI panel screen, as shown in Figure 20.

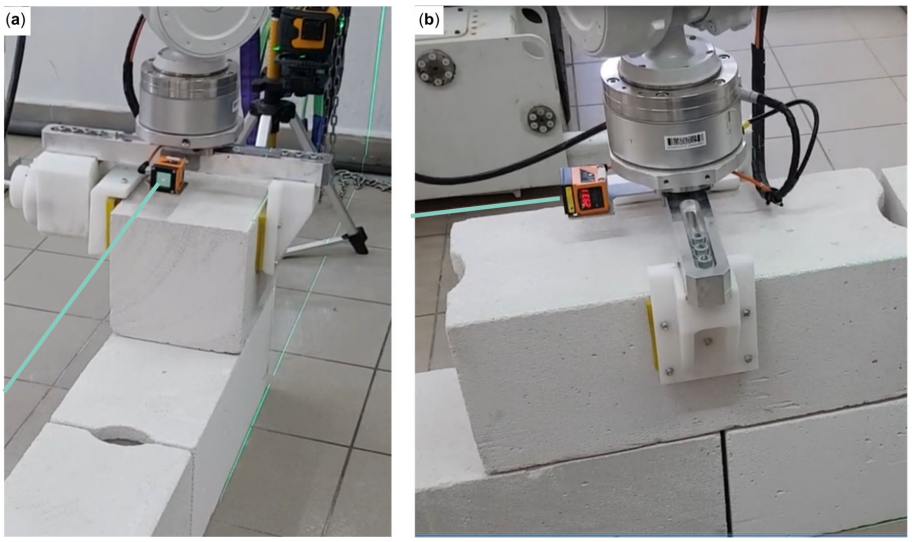


Figure 18. Photos (**a**,**b**) show the use of LRF when a cell block is laid on the wall.

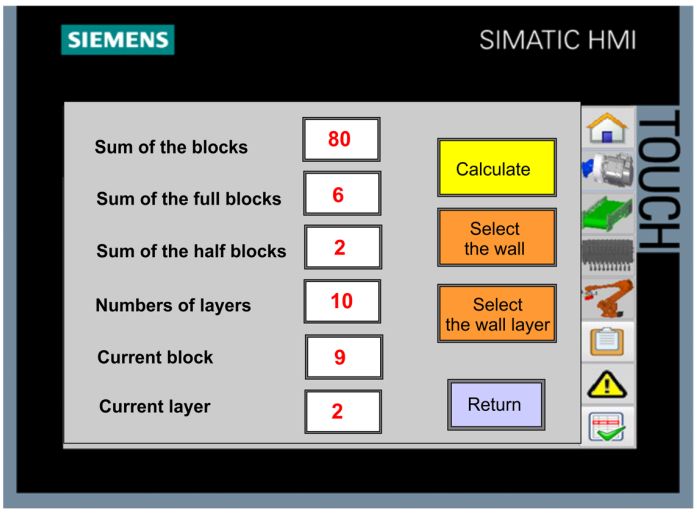


Figure 19. HMI panel screen to select cell blocks on the wall.

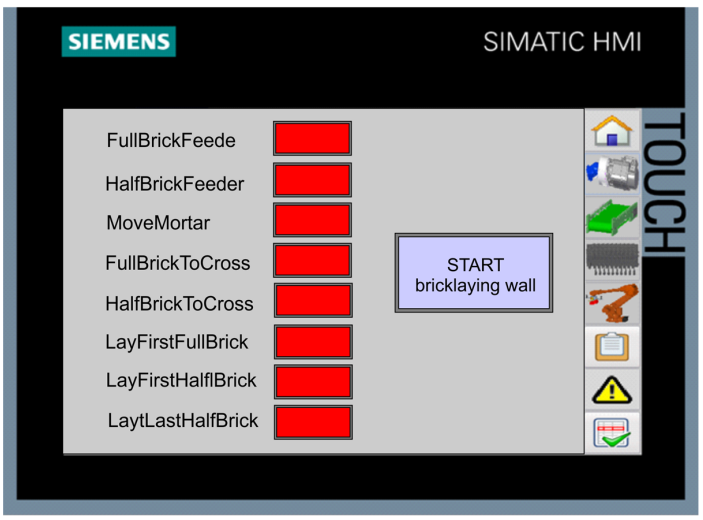


Figure 20. HMI panel screen with bricklaying procedure.

These procedures are as follows [97,98]: FullBrickFeeder—moves to the brick feeder and picks up a full brick, HalfBrickFeeder—moves to the brick feeder and picks up a half brick, MoveMortar—moves to the mortar applicator and applies mortar to the brick; FullBrickToCross—moves the full brick with the applied mortar to the CP; HalfBrickToCross—moves the half a brick with the applied mortar to the CP; SetFirstFullBrick—lays the first full brick on the wall, LayFirstHalflBrick—lays the first half brick on the wall, LayAnBrick—lays the other brick on the wall, LayLastHalfBrick—lays the last half brick on the wall, CrossToBrickFullFeeder—moves from the CP to the brick feeder and picks up a full brick, CrossToHalfBrickFeeder—moves from the CP to the brick feeder and picks up a half brick.

When programming the robot, not only the order of laying the blocks (bricks) is considered, but also their direction of laying on the wall is performed with different positions of the gripper relative to the wall layers, as shown in Figure 21.

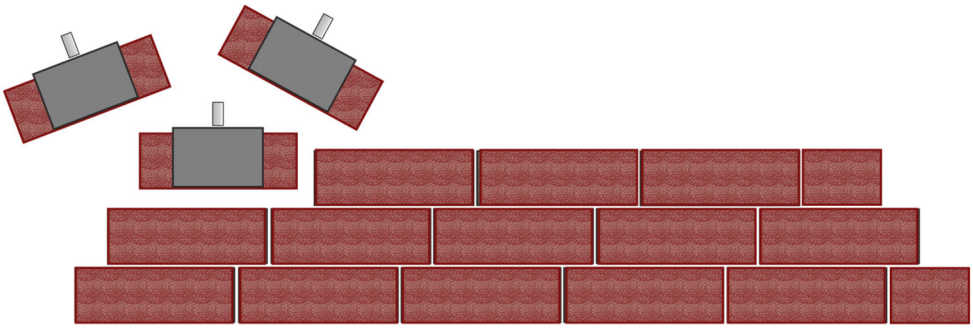


Figure 21. Position of the gripper when laying blocks (bricks) on a wall.

A bricklaying algorithm that combines cross-line laser reference measurements (CLL) with laser range finder (LRF) element position autocorrection. The CLL determines the wall geometry (WL, WH, and WA) and CP cross points that determine the deposit strategy (from above/from the side), whereas the LRF provides live readings of the element distance and rotation angle relative to the wall end, enabling dynamic compensation for "as-built" deviations. The entire process was integrated with a library of robot procedures (intake, mortar application, transport to CP, and deposit) and HMI panels for the parameterization of the process.

The algorithm contains a task.

1. Setting and reference: RBS positioning, TCP/COG teaching, Pi-point recording, starting CLL, measuring WL/WH/WA, determining CP, and introducing BL/BW/BH/TH/TV to HMI.
2. Layout planning: determining the number of layers and FULL/HALF distribution; selecting the placement strategy relative to the CP (if the target point is above, place sideways; if below, from above).
3. Layer loop k: For each element n, perform a pick-up (FULL/HALF), apply the mortar, and transfer it to the CP.
4. LRF auto-calibration: Measure the distance to the end of the wall and the rotation angle around the Z axis; correct the TCP/holder pose.
5. Placement and clamping: Use the appropriate procedure (SetFirstFullBrick, LayFirstHalfBrick, LayAnBrick, and LayLastHalfBrick).
6. Online quality control: After placing the element, check the LRF deviation; if > tolerance, micro-correction or STOP and re-measure; otherwise, proceed to the next element.
7. Layer closing: The reference level (CLL) and TH offsets are updated. If there are subsequent layers, repeat the process; otherwise, generate an HMI report.

Reference code:

```
INIT:
TeachTCP(); SavePiPoints();
CP, WL, WH, WA ← MeasureWithCLL();
BL, BW, BH, TH, TV ← InputBrickAndMortar();
plan ← PlanLayersAndCuts(WL, WH, BL, BH, TH, TV);
mode ← SelectPlacementMode(CP, WA);
FOR k in plan.layers:
  FOR each slot n in plan[k]:
    brickType ← plan[k][n]
    CALL (brickType == FULL ? FullBrickFeeder: HalfBrickFeeder)
    CALL MoveMortar(TH, TV)
    CALL (brickType == FULL? FullBrickToCross: HalfBrickToCross)
    dist, zAngle ← LRF_MeasureToWallEnd()
    pose ← ComputePoseFromCP(dist, zAngle, Pi, mode)
    AdjustTCP(pose)
    if n == 1 and brickType == FULL: CALL SetFirstFullBrick(pose)
    else if n == 1 and brickType == HALF: CALL LayFirstHalfBrick(pose)
    else if IsLastHalf(n): CALL LayLastHalfBrick(pose)
    else: CALL LayAnBrick(pose)
    err ← LRF_CheckAccumulatedError()
    if err > tolerance:
      pose' ← Compensate(err)
      MicroAdjust(pose')
  END
  END
  REPORT ← Summarize(HMI, stats = {counts, cycleTime, maxDev})
```

The integration of the CLL (geometric reference) and LRF (cycle auto-calibration) allows for improved repeatability, reduced programming time, and reduced downtime through micro-adjustments to the trajectories. The algorithm is scalable and can be adapted to various component formats and processing power.

4. Testing the RBS

The programming of the ABB IRB 4600 robot was tested for various bricklaying tasks in laboratory conditions. During the robotic bricklaying tests, the following were checked: the precision and repeatability of the bricklaying, vertical and horizontal deviation of the wall, thickness, and accuracy of filling the vertical and horizontal joints of the wall. Figure 22 shows the test of the robotic bricklaying process under laboratory conditions, which includes picking the cell block from the feeder, applying mortar to the cell block, moving the cell block to the wall, locating the cell block on the wall line, locating the cellular block over the position on the wall, and finally placing the cell block in the wall and pressing it [91,96].

Robotic bricklaying using industrial robot ABB IRB 4600 capabilities was verified during a bricklaying demonstration at a residential building construction site during "STRABAG Innovation Day" and the construction of a hospital emergency department (ER). The RBS was first used for a commercial wall construction contract in an investment project called "Apartments Villa Bogoria" in Warsaw as a service for MURPOL Budownictwo Ltd. (Bielsko-Biała, Poland). Figure 23 shows the bricklaying of the partition wall at the construction site using the RBS. On-site testing of the building showed that the RBS was capable of laying cell blocks of size 24 × 24 × 49 cm and weight 24.4 kg in a cycle time of approximately 42 s. Seven cell blocks are required to build 1 m^2 of wall, and the bricklaying time is approximately 5 min per cell

block. The RBS can build 12 m^2 of wall per hour using 84 cell blocks. Based on these data at 10 h of work per day, the RBS can bricklay 120 m^2 of walls, and with 250 days of work per year, 30,000 m^2 of walls can be bricklayed. The quality of the RBS bricklaying is in line with the standards and guidelines of the Institute of Building Techniques (IBT) [99] and the standard deviation of the building [100].

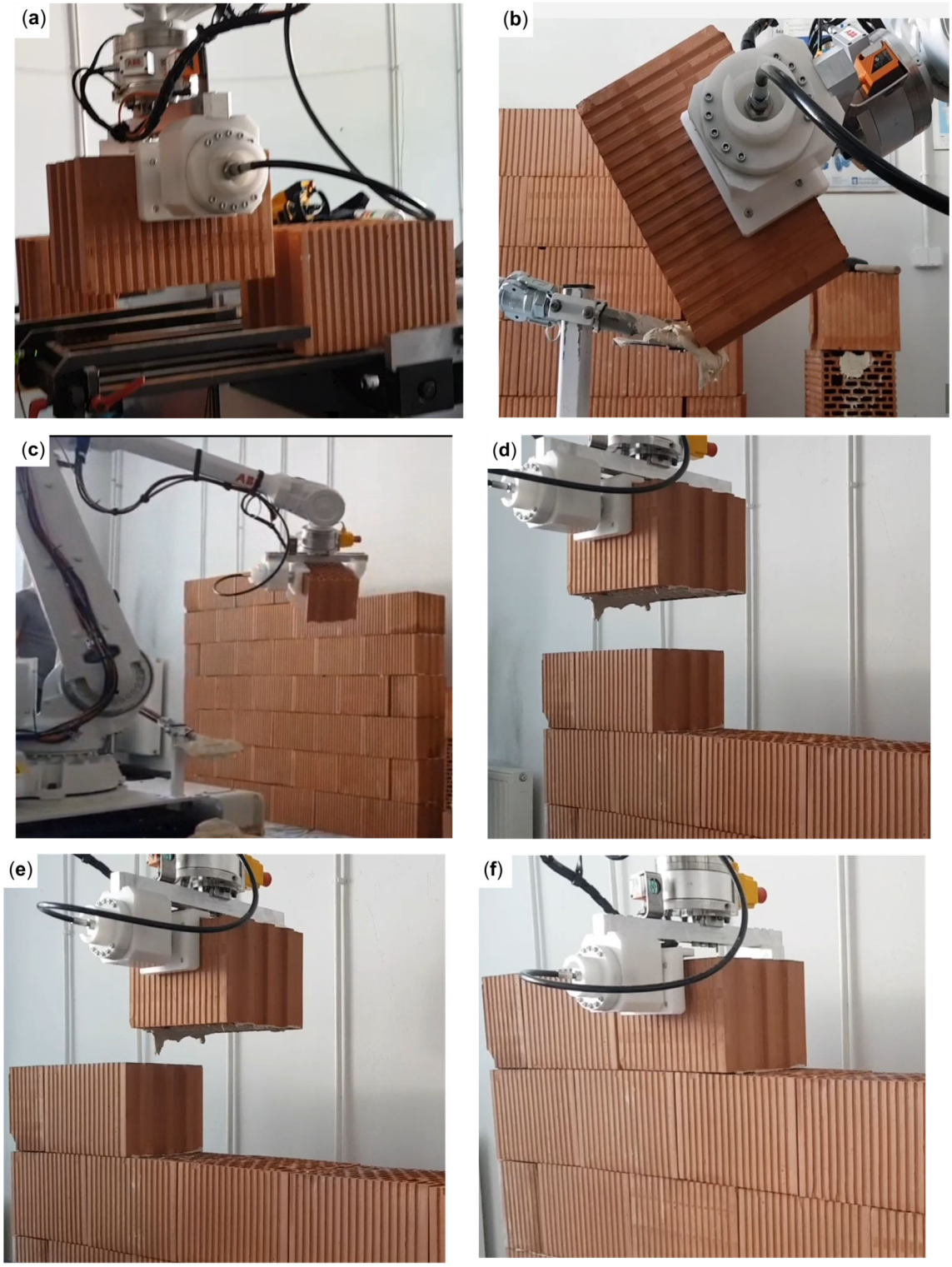


Figure 22. Testing of the bricklaying process under laboratory conditions: (**a**) pick up the cell block from the feeder, (**b**) apply mortar to a cell block, (**c**) move a cell block, (**d**) location of the cell block on the wall line, (**e**) location of the cell block at the place where it was laid, (**f**) lay a cell block on the wall and press it.

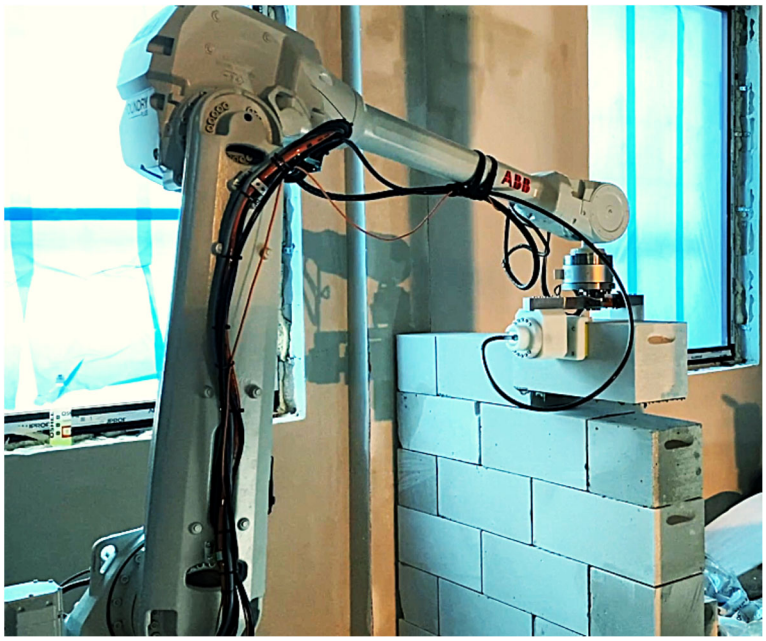


Figure 23. Bricklaying of the partition wall on the construction site using industrial robot ABB IRB 4600.

According to the Temporary Company Catalog of Construction and Conservation Standards [101], a bricklayer can lay eight cell blocks in one hour. This means that the productivity of the RBS bricklayer is more than 10 times higher per hour than that of a bricklayer whose work requires a lot of physical stress that puts their health at risk, such as a spinal injury. Compared to the work of bricklayers, the average accuracy of bricklaying using RBSs is estimated to increase by more than 75%, the amount of rework will decrease by more than 80%, and the number of dangerous tasks will decrease by more than 75%. However, keep in mind that these numbers represent estimated potential and controlled pilot results; real-world performance can vary based on the complexity of the building site, specific masonry materials used, and robotic technology.

The statistical evaluation of the measurement series according to the construction standards should be in the following range:

Wall verticality: The maximum deviation of the wall surface from the vertical plane is ±10 mm per 2 m of height.

Wall thickness: The wall thickness varied within a tolerance of ±5 mm at all the measurement points.

Openings (windows and doors): For an opening width of 1.0 m, the dimensional deviations were +6 mm/−3 mm. For an opening height of 1.0 m, the deviations were +15 mm/−10 mm

Table 2 summarizes the measurement results of the walls laid by industrial robot ABB IRB 4600. Measurements of the individual dimensions of the walls show that robotic bricklaying has a much lower range of standard deviation compared to the construction standards for labor bricklaying. The results indicate high-quality robotic bricklaying with good repeatability. The deviations were small and stable and within the tolerances used for this type of bricklaying work.

Figure 24 shows the dimensional deviations and distribution of the individual wall measurements.

Based on standards [102,103], the risk assessment and hazards of RBSs were analyzed, such as software, online teaching, start, operator access, and misuse. The RBS assessment considered the safety hazards of HRI on construction sites using a report from the Center

for Construction Research Training (CPWR) [104], which concerns the identification and analysis of threats in construction sites.

Table 2. Summary of the measurement results of the walls laid by industrial robot ABB IRB 4600.

Measurement Category	Size n	Mean	Median	STD	Min	Max	Range
Wall verticality (per 2 m) in mm	40	0.1	−0.18	1.61	−2.86	3.48	6.34
Wall thickness in mm	40	0.17	0.07	1.63	−2.72	2.82	5.54
Opening width (1 m) in mm	40	0.62	0.62	1.08	−1.25	2.63	3.88
Opening height (1 m) in mm	40	−0.08	−0.27	1.01	−1.43	1.76	3.19

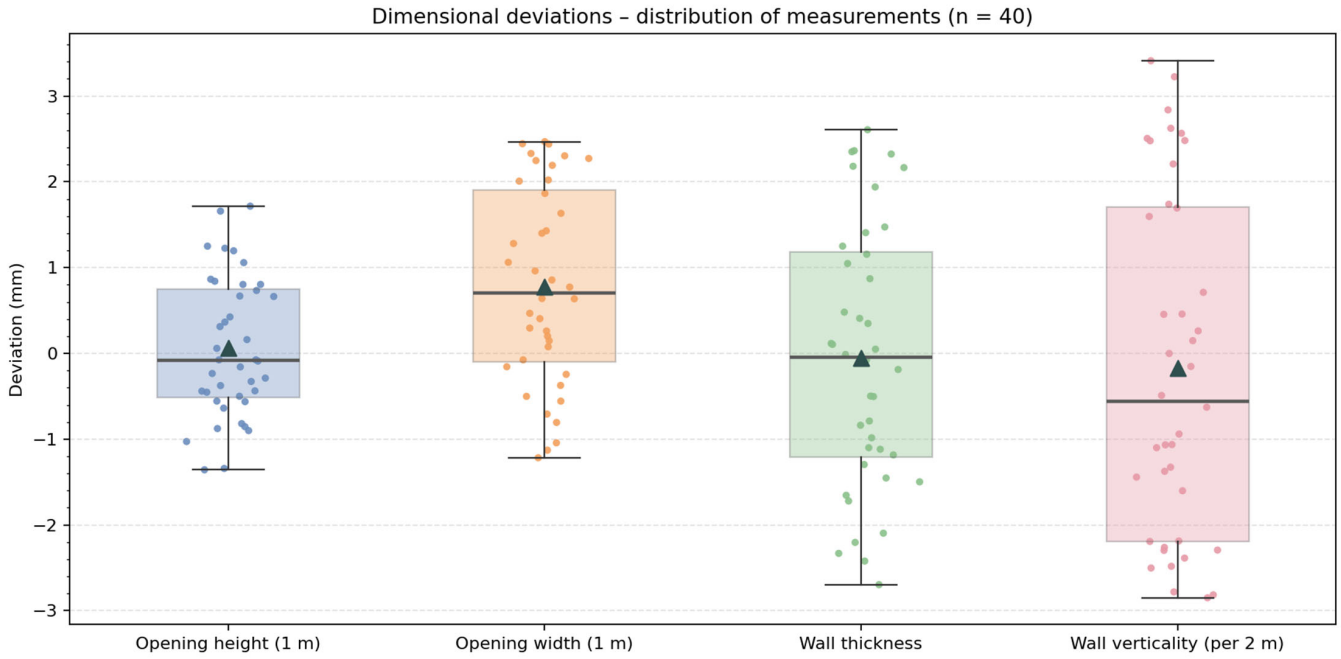


Figure 24. Dimensional deviations and distribution of the individual wall measurements.

5. Discussion

Robotic bricklaying is consistent with sustainable development goals because of its economic benefits, such as increased efficiency and speed of work, high repeatability and quality of work, lower rework costs, reduced material consumption, minimal material waste, reduced labor costs, and improved work quality in unfavorable conditions. Reducing the completion times of construction projects results in a shorter investment cycle, a faster return on investment, and reinvestment of profits.

Robotic bricklaying will lead to social benefits, such as solving the housing crisis and fostering social and mass housing development, because apartments will be delivered to the public faster and with better quality, housing availability will increase, and living conditions and quality of life will improve.

Robotic bricklaying will create attractive jobs in the construction industry, improving the skills and professional development of construction workers in robotics and digital technologies.

RBS technology tightly couples BIM (Autodesk Revit) with the offline programming of ABB RobotStudio and then bridges the reality of the construction site via online CLL and LRF self-calibration. This robotic bricklaying technology is well-suited for BIM-managed apartment projects and robotic bricklaying when frequent on-site changes are made. Figure 25 shows an RBS bricklaying technology flowchart that uses digital BIM tools to create, edit, and view building models in a 3D environment and the actual robotic bricklaying process.

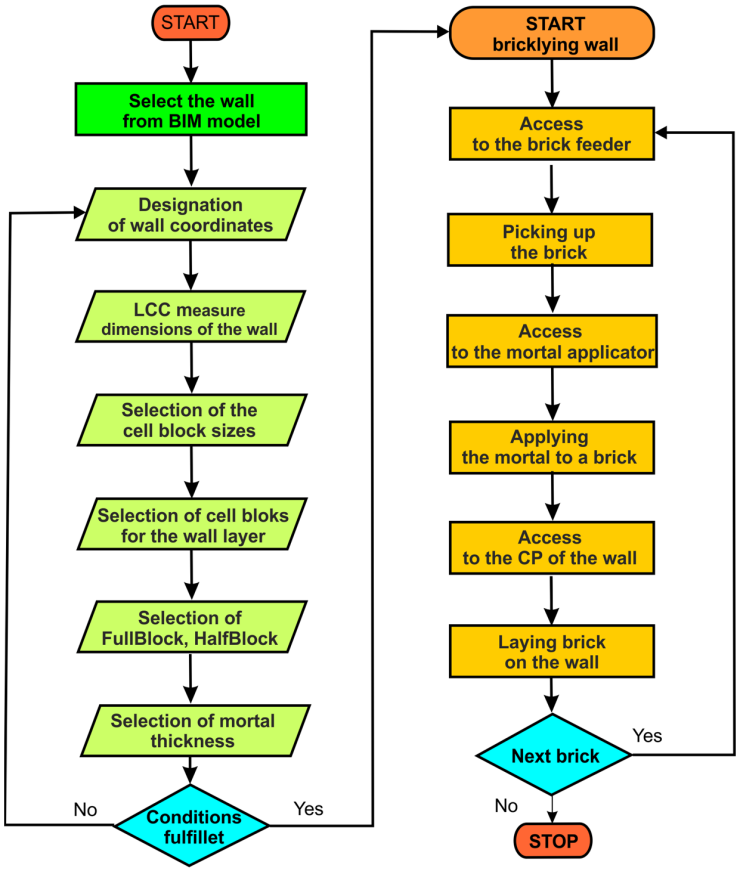


Figure 25. Flowchart of the RBS bricklaying technology process.

Although BIM in construction projects in Poland is already a market standard, particularly in large infrastructure investments and private commercial projects, there is a lack of a uniform BIM mandate in the public sector, varying levels of digital maturity between companies, the so-called "digital gap" among smaller contractors who still use analog tools, and a shortage of BIM information and coordination specialists [105,106].

The impact of robotic bricklaying on sustainable construction (sustainable buildings) is to reduce the negative environmental impact of construction by reducing the consumption of materials, mortar, and material waste. Robotic bricklaying reduces errors and rework, resulting in reduced material and energy waste generation. Robotic bricklaying is integrated with CE, allowing the laying of unusually shaped bricks, processing of recycled materials, and support of waste reduction and reuse of raw materials.

The implementation of bricklaying robots at construction sites in Poland encounters various obstacles, such as:

1. Purchasing and integrating a bricklaying robot (hardware, software, training, and logistics) represents a significant expense, particularly for small- and medium-sized companies. In the construction industry, high investment costs are a key factor that restricts innovation.
2. Bricklaying robots require adapting the workstation to existing execution processes and properly preparing the construction site, which is not ready for integration with robotics and digital technology.
3. BIM, CDE, and data management platforms require investments in cybersecurity, organizational changes, and IT infrastructure updates, which are additional barriers, particularly for smaller companies.
4. The construction site is an environment characterized by high variability in the topography and location of the building, which is susceptible to change and logistically

limited, hindering the effective operation of bricklaying robots, especially compared to factory prefabrication, where conditions are stable and predictable.

5. There is a shortage of robotics-specialized workers who can supervise the automated processes. There is already a significant shortage of construction professionals in Poland (approximately 150,000 people), indicating even greater difficulty in finding technical specialists in the field of robotics.
6. Construction work is often perceived as a threat to the reluctance to work, leading to the need for additional training and adaptation measures. Skeptical attitudes toward innovative robotic technologies have been observed among engineers, construction workers, management staff, stakeholders, and clients.
7. Robotization in the Polish construction industry is still in the early stages of development; there are no standardized implementation procedures, a broad service network, or practical experience from a large number of investments. The complexity of the supply chains for construction materials is unsuitable for robotic bricklaying. There is a diversity of regional construction markets, labor and material costs, and legal regulations in the country that must be considered.

The summary presents a detailed SWOT analysis of bricklaying robotization in Poland, prepared based on current information on bricklaying robots, trends in construction robotization, and technological and organizational barriers identified in the literature and industry reports.

S—Strengths
S.1. High efficiency, quality, and precision of the robotic bricklaying.
S.2. Robots relieve workers of physical burdens and improve work ergonomics.
S.3. Robots solve the problem of the shortage of skilled bricklayers, and robotization can reduce the dependence of investments on labor availability.
S.4. Robots can operate continuously and predictably, thereby reducing unexpected interruptions during bricklaying.
W—Weaknesses
W.1. High capital costs are required to purchase, implement, and integrate these robots.
W.2. Integration difficulties and the need for digital infrastructure are both challenges.
W.3. Limited adaptation of robots to irregular building architectures is observed.
W.4. Lack of specialists to operate and service robots
O—Opportunities
O.1. The growing need to shorten investment lead times
O.2. Dynamic development of artificial intelligence (AI) and robotics technologies
O.3. Government and EU support for digitalization and automation related to Industry 4.0/5.0 and energy and environmental transformation.
O.4. Possibility of using robots in difficult and hazardous environments
O.5. There is growing investor interest in ensuring stable bricklaying quality and minimizing construction risks.
T—Threats
T.1. Employee resistance and fear of job losses
T.2. High variability of construction site conditions
T.3. High technological, technical, and service risks.
T.4. Competition for the robotic bricklaying market from prefabrication, 3D printing, and other innovative construction technologies.

Economic evaluation of robotic bricklaying.

The economic feasibility assessment of robotization in the construction bricklaying sector considers the following costs:

1. Development costs include the total costs associated with the labor, resources, and infrastructure used to research, experiment, and evaluate various robotic system solutions.
2. Investment costs include components such as depreciation over time and interest paid on the investment.
3. Costs of configuring IT and technical systems to meet the requirements for the installation of robots and construction equipment at construction sites.
4. Maintenance and repair costs of robots and construction equipment.
5. Operating costs include materials, energy, wages, and other components related to the operation of robots and construction equipment.
6. Indirect costs include overhead and management costs associated with the implementation of robotic technology.

Robotic bricklaying can be economically feasible even when labor is inexpensive, but only under the right conditions, such as labor shortages, high productivity requirements, or multi-project amortization. Where cheap human labor is plentiful and predictable, the economics currently favor manual labor [107].

Experience shows that ROI improves only when robots are used in many projects and when the cost of robotic hardware decreases over time. This implies that large firms managing multiple projects benefit the most from the program. Small contractors cannot justify their investments unless shared robotics or leasing services become available.

Robotic bricklaying improves consistency, reduces errors, and enhances safety. Robotic systems that use BIM integration and AI-driven quality control significantly reduce structural variability and waste generation. The analysis of bricklaying robotics indicates that robotics can reduce costs through the reduction of rework and the use of more efficient materials. These savings can contribute to long-term economic feasibility, even when the labor is inexpensive. Robots can be used by low-cost labor markets if they cannot find enough skilled workers to meet their requirements. In markets where project timelines are tight or skilled labor shortages exist, productivity gains may offset low wage levels.

However, robotics cannot achieve a rapid ROI because of the small wage discrepancy in low-wage labor markets. Robots require additional expenditures for maintenance, calibration, transportation, and operator training. When labor is cheap, the implementation of robotics is rarely justified by directly replacing it.

Table 3 shows a comparison of the projected cost of bricklaying for human labor and robots, which was calculated for ROI considering 280 annual robot days, 1821 days per project using robots, and eight deployments per year.

Table 3. Comparison of the projected costs of bricklaying by human labor and industrial robots.

Metrics	Manual	Robotic
Total blocks (incl. waste)	6,180,000	6,120,000
Daily output (blocks/day)	1400	3360
Project duration (days)	4414	1821
Direct labor cost in EU	4,414,286	1,092,857
Overhead/supervision cost in EU	882,857	728,571
Materials/consumables cost in EU	618,000	734,400
Ownership and maintenance cost in EU	0	25,000
Mobilization cost in EU	0	25,000
Total project cost in EU	5,915,143	2,580,829
Net ROI in EU		3,334,314

Architectural limitations of robotic bricklaying.

1. Limited ability to handle irregular or free-form geometries. Most bricklaying robots excel in repetitive and regular patterns, such as straight walls, level courses, and consistent joints. Bricklaying robots struggle with non-uniform bricks, salvaged materials, and inconsistent surfaces that require complex sensing and adjustment. Unconventional curves and freeform geometries, which require real-time recalculation and detection capabilities, are challenging for current robotic bricklaying systems to handle. Large-scale irregular architectural designs, where a limited robot workspace or reach becomes insufficient without rails or multirobot coordination, are challenging.
2. Constraints of the workspace and kinematics of the robots. Industrial robots have fixed reach and optimal operating zones, which restrict their DoF. Industrial robots are limited in their workspace and can only lay bricks in one position, which limits the size and shape of the brick walls. Repositioning robots to follow complex wall geometries is time-consuming and inefficient. The use of robots in flexible architectures with large or multifaceted structures is limited to a few applications.
3. Difficulty with intricate and custom bricklaying. Industrial robots are not well-suited for bespoke brick detailing, sculptural forms, or variable bond patterns that require artistic judgment. Renovations or buildings with unique architectural requirements often rely on skilled humans because robots lack adaptive decision-making and tactile feedback capability.
4. The constraints of environmental and site conditions are as follows: industrial robots face uneven terrain, cluttered sites, and vibration problems that disrupt their precise placement. Robotic bricklaying is not weather-resistant, particularly when fine tolerances or wet mortar are required. Atmospheric conditions, such as wind, temperature, and humidity, limit the operation of robots at construction sites.
5. Materials and mortar constraints. Architectural designs that depend on specific materials or bonding methods may not be compatible with robotic operations. Robots often require uniform blocks to maintain consistent grip and placement accuracies. Some bricklaying systems rely on special blocks or adhesives, limiting their architectural integration with traditional masonry practices and local material standards. Gripping and manipulating irregular bricklaying materials remain technical challenges in robot bricklaying.

6. Conclusions

This study demonstrates that robotic bricklaying technologies are being used practically on Polish construction sites, with 2025 marking a key milestone and the first commercial deployment of a mobile RBS. Although robotization remains in the early development phase, increasing labor shortages, tight project schedules, and the growing adoption of BIM and CDE platforms render automated masonry an increasingly viable and necessary solution for the construction sector.

The RBS effectively supports large-scale masonry tasks by accelerating bricklaying, improving dimensional accuracy, and reducing material waste. Through integration with BIM, RobotStudio simulation, and on-site laser-based calibration (CLL and LRF), the system enables digital–physical alignment, real-time adaptation to construction site conditions, and consistent masonry quality. While industrial robots remain less suitable for highly irregular geometries, complex architectural details, or renovation work, the RBS excels in repetitive modules and long linear walls commonly found in residential and public buildings.

This project provides valuable information on the design, implementation, and operation of bricklaying robots under real-world construction conditions. It highlights the technical, organizational, and economic challenges, including high investment costs, the need for digital-ready sites, workforce upskilling, and limited standardization of robotic

workflows. However, the deployment of RBSs in Poland shows that robotic masonry can contribute significantly to sustainable construction by reducing waste and energy use, improving ergonomics and safety, and improving the quality of construction according to the ESG principles.

In general, the RBS represents a fundamental step toward broader digitalization and automation of construction in Poland. With continued technological development, workforce training, and the integration of advanced sensing and AI tools, robotic bricklaying can become a practical, scalable, and economically competitive solution for modern construction projects.

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References

1. Dindorf, R.; Wos, P. Challenges of robotic technology in sustainable construction practice. *Sustainability* **2024**, *16*, 5500. [CrossRef]
2. Xu, L.; Zhang, Y.; Liu, M.; Li, Y.; Li, Y.; Yu, Y.; Tang, Q.; Weng, S.; Sang, K.; Lin, G. Robotics in the construction industry: A bibliometric review of recent trends and technological evolution. *Appl. Sci.* **2025**, *15*, 6277. [CrossRef]
3. Keles, C.; Cruz Rios, F.; Hoque, S. Digital technologies and circular economy in the construction sector: A Review of lifecycle applications, integrations, potential, and limitations. *Buildings* **2025**, *15*, 553. [CrossRef]
4. Preidel, C.; Borrmann, A.; Mattern, H.; König, M.; Schapke, S.E. Common Data Environment. In *Building Information Modeling*; Borrmann, A., König, M., Koch, C., Beetz, J., Eds.; Springer: Cham, Switzerland, 2018.
5. Radl, J.; Kaiser, J. Benefits of implementation of common data environment (CDE) into construction projects. *IOP Conf. Ser. Mater. Sci. Eng.* **2019**, *471*, 022021. [CrossRef]
6. Jaskula, K.; Kifokeris, D.; Papadonikolaki, E.; Rovas, D. Common data environments in construction: State-of-the-art and challenges for practical implementation. *Constr. Innov.* **2025**, *25*, 1522–1541. [CrossRef]
7. Chen, Z.; Wang, H.; Chen, K.; Song, C.; Zhang, X.; Wang, B.; Cheng, J.C.P. Improved coverage path planning for indoor robots based on BIM and robotic configurations. *Autom. Constr.* **2024**, *158*, 105160. [CrossRef]
8. Zhang, J.; Luo, H.; Xu, J. Towards fully BIM-enabled building automation and robotics: A perspective of lifecycle information flow. *Comput. Ind.* **2022**, *135*, 103570. [CrossRef]
9. Anane, W.; Iordanova, I.; Ouellet-Plamondon, C. Building information modeling (BIM) and robotic manufacturing technological interoperability in construction—A cyclic systematic literature review. *Digit. Manuf. Technol.* **2023**, *3*, 1–90. [CrossRef]
10. Francis, S.; Divyamol, M.V.; Manuel, S.K. Three Dimensions of sustainable development: A holistic approach to a better future. *Int. J. Multi. Res.* **2025**, *7*, 1–11. [CrossRef]
11. Delgado, J.M.D.; Oyedele, L.; Demian, P.; Beach, T. A research agenda for augmented and virtual reality in architecture, engineering and construction. *Adv. Eng. Inf.* **2020**, *45*, 101122. [CrossRef]
12. Construction Robot Market. Available online: https://www.databridgemarketresearch.com/reports/global-construction-robot-market (accessed on 1 March 2026).
13. *Annual Review of the BRE Trust, 2019–2020*; BRE Trust: Watford Hertfordshire, UK, 2020.
14. *Introduction to LEED for Design and Construction*; U.S. Green Building Council: Atlanta, GA, USA, 2024.
15. *Building Materials and Sustainability Report*; DGNB GmbH: Stuttgard, Germany, 2022.
16. *HQE (High Environmental Quality) Certification, The French Green Certification*; HQE-GBC Alliance: Paris, France, 2024.
17. *WELL Certification Guidebook*; International Well Building Institute: New York, NY, USA, 2022.
18. Global Bricklaying Robot Market Size, Share, and Trends Analysis Report—Industry Overview and Forecast to 2032. Available online: https://www.databridgemarketresearch.com/reports/global-bricklaying-robot-market (accessed on 1 May 2024).
19. Bricklaying Robot Market. Available online: https://www.marketresearchfuture.com/reports/bricklaying-robot-market-35843 (accessed on 1 May 2024).
20. ABB Robotics Advances Construction Industry Automation to Enable Safer and Sustainable Building. Available online: https://new.abb.com/news/detail/78359/abb-robotics-advances-construction-industry-automation-to-enable-safer-and-sustainable-building (accessed on 20 May 2021).

21. ETH Zurich Robots Use a New Digital Construction Technique to Build Timber Structures. Available online: https://www.dezeen.com/2018/04/16/robotic-construction-architecture-technology-eth-zurich-switzerland-spatial-timber-assemblies (accessed on 16 April 2018).
22. Petersen, K.H.; Napp, N.; Stuart-Smith, R.; Rus, D.; Kovac, M. A review of collective robotic construction. *Sci. Robot.* **2019**, *4*, eaau8479. [CrossRef] [PubMed]
23. Leder, S.; Achim Menges, A. Architectural design in collective robotic construction. *Auto. Constr.* **2023**, *156*, 105082. [CrossRef]
24. Liu, Y.; Alias, A.H.; Haron, N.A.; Bakar, N.A.; Wang, H. Robotics in the construction sector: Trends, advances, and challenges. *J. Intell. Robot. Syst.* **2024**, *110*, 72. [CrossRef]
25. Pan, M.; Linner, T.; Pan, W.; Cheng, H.; Bock, T. A framework of indicators for assessing construction automation and robotics in the sustainability context. *J. Clean Prod.* **2018**, *182*, 82–95. [CrossRef]
26. Garcés, G. Advances in human-robot collaboration (HRC) in Construction 5.0 for building construction: A bibliometric and systematic literature review. *J. Inf. Technol. Constr.* **2025**, *30*, 1244–1276. [CrossRef]
27. Marinelli, M. From Industry 4.0 to Construction 5.0: Exploring the Path towards Human–Robot Collaboration in Construction. *Systems* **2023**, *11*, 152. [CrossRef]
28. Pan, W. Methodological Development for Exploring the Potential to Implement On-Site Robotics and Automation in the Context of Public Housing Construction in Hong Kong. Ph.D. Thesis, Lehrstuhl für Baurealisierung und Baurobotik, Technische Universität München, München, Germany, 2020.
29. Yahya, M.Y.B.; Yin, L.H.; Yassin, A.B.M.; Omar, R.; Robin, R.O.; Kasim, N. The challenges of the implementation of construction robotics technologies in the construction. *MATEC Web Conf.* **2019**, *266*, 05012. [CrossRef]
30. Harinarain, N.; Caluza, S.; Dondolo, S. Bricklaying robots in the South African construction industry: The contractors perspective. In *Proceedings of the 37th Annual ARCOM Conference, Leeds, UK, 6–7 September 2021*; Scott, L., Neilson, C.J., Eds.; Association of Researchers in Construction Management: Glasgow, UK, 2021; pp. 36–45.
31. Selvam, V. Advancing sustainable construction in India: Exploring standardization, challenges, and opportunities in 3D printing, robotics, and automation integration for large-scale projects. *J. Con. Buil. Mat. Eng.* **2025**, *11*, 59–80.
32. Mosly, I. Construction Cost-Influencing Factors: Insights from a Survey of Engineers in Saudi Arabia. *Buildings* **2024**, *14*, 3399. [CrossRef]
33. Carra, G.; Argiolas, A.; Bellissima, A.; Niccolini, M.; Ragaglia, M. Robotics in the construction industry: State of the art and future opportunities. In *Proceedings of the 35th International Symposium on Automation and Robotics in Construction, Berlin, Germany, 20–25 July 2018;* The International Association for Automation and Robotics in Construction (IAARC): Oulu, Finland, 2018; pp. 866–873.
34. Xiao, B.; Chen, C.; Yin, X. Recent advances of robotics in construction. *Autom. Constr.* **2022**, *144*, 104591. [CrossRef]
35. Arabi, K. Construction Robots in 2024: A Comprehensive Guide. 11 June 2023. Available online: https://neuroject.com/construction-robots (accessed on 11 June 2023).
36. Bock, T.; Linner, T. Site Automation. In *Automated/Robotic On-Site Factories*; Cambridge University Press: New York, NY, USA, 2016.
37. Parascho, S. Construction robotics: From automation to collaboration. *Annu. Rev. Control Robot. Auton. Syst.* **2023**, *6*, 183–204. [CrossRef]
38. Melenbrink, N.; Werfel, J.; Menges, A. On-site autonomous construction robots: Towards unsupervised building. *Auto. Cons.* **2020**, *119*, 103312. [CrossRef]
39. Craig, M. Robots in Construction: Bricklaying. Available online: https://www.azorobotics.com/Article.aspx?ArticleID=654 (accessed on 12 December 2023).
40. Mitterberger, D.; Jenny, S.E.; Vasey, L.; Lloret-Fritschi, E.; Aejmelaeus-Lindström, P.; Gramazio, F.; Kohler, M. Interactive robotic plastering: Augmented interactive design and fabrication for on-site robotic plastering. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems, New Orleans, LA, USA, 29 April 2022–5 May 2022*; Association for Computing Machinery: New York, NY, USA, 2022; Volume 174, pp. 1–18.
41. French Startup Develops a Painting Robot. Available online: https://www.paintsquare.com/news/view/?25927 (accessed on 6 January 2023).
42. Pham, T.H.; Lim, J.H.; Pham, Q.-C. Robotic 3D-Printing for building and construction. In *Proceedings of the 2nd International Conference on Progress in Additive Manufacturing (Pro-AM 2016), Singapore, 16–19 May 2016*; Research Publishing: Singapore, 2016; pp. 300–305.
43. Demolition Robots. Available online: https://www.raseq.com/demolition-robots (accessed on 1 January 2024).
44. Robotics: Who Are the Leaders in Welding Robots for the Construction Industry? Available online: https://www.worldconstructionnetwork.com/data-insights/innovators-robotics-welding-robots-construction/?cf-view (accessed on 1 December 2023).
45. Skibniewski, M.J.; Wooldridge, S.C. Robotic materials handling for automated building construction technology. *Auto. Constr.* **1992**, *1*, 251–266. [CrossRef]
46. Coxworth, B. Robotic Excavator Builds a Giant Stone Wall with No Human Assistance. Available online: https://newatlas.com/robotics/heap-autonomous-robotic-excavator-stone-wall (accessed on 22 November 2023).

47. Uborevich-Borovskaya, A. *From Design to Automated Assembly: Applying Industrial Robots to Large-Scale Digital Discrete Design*; The Bartlett School of Architecture, University College London: London, UK, 2017.
48. Bidgoli, A. Toward an Integrated Design-Making Approach in Architectural Robotics. Master's Thesis, The Graduate School College of Arts and Architecture, The Pennsylvania State University, University Park, PA, USA, 2016.
49. Nguyen, M.N. Drivers of innovation towards sustainable construction: A study in a developing country. *J. Build. Eng.* **2023**, *80*, 107970. [CrossRef]
50. Maqbool, R.; Arul, T.; Saleha Ashfaq, S. A mixed-methods study of sustainable construction practices in the UK. *J. Clean. Prod.* **2023**, *430*, 139087. [CrossRef]
51. Araújo, A.G.; Carneiro, A.M.P.; Palha, R.P. Sustainable construction management: A systematic review of the literature with meta-analysis. *J. Clean. Prod.* **2020**, *256*, 120350. [CrossRef]
52. Dörfler, K.; Sandy, T.; Giftthaler, M.; Gramazio, F.; Kohler, M.; Buchli, J. Mobile robotic brickwork. In *Robotic Fabrication in Architecture, Art and Design*; Reinhardt, D., Saunders, R., Burry, J., Eds.; Springer: Cham, Switzerland, 2016.
53. Buchli, J.; Giftthaler, M.; Kumar, N.; Lussi, M.; Sandy, T.; Dörfler, K.; Hack, N. Digital in situ fabrication. Challenges and opportunities for robotic in situ fabrication in architecture, construction, and beyond. *Cem. Conc. Res.* **2018**, *112*, 66–75. [CrossRef]
54. Helm, V. In-Situ-Fabrikation. Ph.D. Thesis, Academy of Media Arts Cologne, Köln, Germany, 2014.
55. Chea, C.P.; Bai, Y.; Pan, X.; Arashpour, M.; Xie, Y. An integrated review of automation and robotic technologies for structural prefabrication and construction. *Transp. Saf. Environ.* **2020**, *2*, 81–96. [CrossRef]
56. Zhao, J.; Wei, S.; Sun, X.; Ji, J. Kinematics and trajectory planning of the masonry robot. *J. Auton. Veh. Sys.* **2022**, *2*, 031005. [CrossRef]
57. Usmanov, V.; Illetsko, J.; Sulc, R. Digital plan of brickwork layout for robotic bricklaying technology. *Sustainability* **2021**, *13*, 3905. [CrossRef]
58. Dakhli, Z.; Lafhaj, Z. Robotic mechanical design for brick-laying automation. *Cogent Eng.* **2017**, *4*, 1361600. [CrossRef]
59. Masri, A.A.; da Costa, B.B.F.; Vasco, D.; Boer, D.; Haddad, A.N.; Najjar, M.K. Roles of robotics in architectural and engineering construction industries: Review and future trends. *J. Build. Des. Env.* **2024**, *2*, 28029.
60. Vidovszky, I.; Pem, A. Analyses of automated bricklaying workflow regarding time and arrangement. *IOP Conf. Ser. Mater. Sci. Eng.* **2022**, *1218*, 012004. [CrossRef]
61. Bricklaying Robot for the First Time in the Czech Republic and for the Construction by GEMO. Available online: https://www.gemo.cz/en/aktuality/bricklaying-robot-for-the-first-time-in-the-czech-republic-and-on-the-construction-by-gemo (accessed on 11 December 2023).
62. Liszka, A. Pierwszy Budynek w Polsce Murowany Przez Robota. Available online: https://www.propertydesign.pl/architektura/104/pierwszy_budynek_w_polsce_murowany_przez_robota,52560.html (accessed on 8 November 2025).
63. Bricklaying Robot Is the Future of Masonry. Available online: https://www.ballast-nedam.com/news/2024/the-bricklaying-robot-is-the-future-of-masonry (accessed on 8 November 2025).
64. Construction Automation's Brick Laying Robot Builds House. Available online: https://www.yorkpress.co.uk/news/18773907.construction-automations-brick-laying-robot-builds-house (accessed on 7 October 2020).
65. Semi-Automated Robot—Sam100. Available online: https://www.planswift.com/blog/semi-automated-robot-sam100 (accessed on 23 January 2019).
66. Robotic Construction Is Here. Available online: https://www.fbr.com.au/view/hadrian-x (accessed on 10 December 2023).
67. Monumental's Bricklaying Robot Fits Through Doors, Automates Construction. Available online: https://3dprint.com/307360/monumentals-bricklaying-robot-fits-through-doors-automates-construction (accessed on 26 February 2024).
68. ABB and Cosmic Use AI-Powered Robots to Rebuild Homes in Los Angeles Area. Available online: https://www.automate.org/robotics/news/abb-and-cosmic-use-ai-powered-robots-to-rebuild-homes-in-los-angeles-area (accessed on 8 June 2025).
69. ABB and ETH Extend Partnership to Advance Research into the Future of Robotics. Available online: https://new.abb.com/news/detail/75886/abb-and-eth-extend-partnership-to-advance-research-into-the-future-of-robotics (accessed on 22 March 2022).
70. Usmanov, V.; Bruzl, M.; Svoboda, P.; Sulc, R. Modelling of industrial robotic brick system. In *Proceedings of the 34th International Symposium on Automation and Robotics in Construction (ISARC2017), Taipei, Taiwan, 28 June–1 July 2017*; The International Association for Automation and Robotics in Construction (IAARC): Oulu, Finland, 2017; pp. 1013–1020.
71. Víctor, B.C.D.; Andree, D.A.P.; Sandra, R.D.; Lisette, L.P.K. Design of an assembly concrete brick that facilitates the laying of bricks with the KUKA robot in the absence of an automated system in the construction of masonry walls. In *Proceedings of the 2023 Congreso Internacional de Innovación y Tendencias en Ingeniería (CONIITI), Bogotá, Colombia, 4–6 October 2023*; IEEE: New York, NY, USA, 2023; pp. 1–6.
72. Ruttico, P.; Pacini, M.; Beltracchi, C. BRIX: An autonomous system for brick wall construction. *Constr. Robot.* **2024**, *8*, 10. [CrossRef]
73. Green Brick Robot with Japanese Fanuc Controller Automatic Brick Stack. Available online: https://www.bricmaker.com/Green-Brick-Robot-with-Japanese-Fanuc-Controller-Automatic-Brick-Stack-p.html (accessed on 22 December 2025).
74. Motoman Robots in the Construction Industry. Available online: https://www.yaskawa.pl/use-cases/industries/industry/budownictwo_i11036 (accessed on 20 January 2026).

75. Dindorf, R. *Development and Demonstration of a Robotic Bricklaying and Plastering System for Use in the Construction Industry*; Research Project; Number POIR.04.01.02-00-0045/18-00 of the National Centre for Research and Development; Kielce University of Technology: Kielce, Poland, 2018.
76. Dindorf, R.; Wos, P. Innovative solution of mobile robotic unit for bricklaying automation. *J. Civil Eng. Trans* **2022**, *4*, 21–32. [CrossRef]
77. *Product Specification ABB IRB 4600*; ABB AB Robotics Products: Västerås, Sweden, 2019.
78. *Application Manual of FlexPendant SDK*; ABB AB Robotics Products: Västerås, Sweden, 2012.
79. Dindorf, R.; Takosoglu, J.; Woś, P.; Chlopek, L. Hydraulic modules of the mobile robotic bricklaying system. In *International Scientific-Technical Conference on Hydraulic and Pneumatic Drives and Control NSHP 2023: Advances in Hydraulic and Pneumatic Drives and Control 2023*; Stryczek, J., Wawrzynska, U., Eds.; Lecture Notes in Mechanical Engineering; Springer: Cham, Switzerland, 2024; pp. 174–183.
80. Dindorf, R.; Takosoglu, J.; Wos, P.; Chlopek, L. *Industrial Design Wp.30256. Tracked Transporter*; Kielce University of Technology: Kielce, Poland, 2022.
81. Dindorf, R.; Takosoglu, J.; Wos, P.; Chlopek, L. *Industrial Design Wp.30764. Tracked Transporter Housing*; Kielce University of Technology: Kielce, Poland, 2022.
82. Dindorf, R. Functional safety of the hydraulic drive control system of a tracked undercarriage. *Archi. Auto. Eng.* **2024**, *103*, 21–31. [CrossRef]
83. Safety of Machinery. Safety-Related Parts of Control Systems Part 1: General Principles for Design. *ISO 13849-1:2023*; ISO: Geneva, Switzerland, 2023. Available online: https://www.iso.org/standard/73481.html (accessed on 10 April 2023).
84. Hauke, M.; Schaefer, M.; Apfeld, R.; Boemer, T.; Huelke, M.; Borowski, T.; Büllesbach, K.-H.; Dorra, M.; Foermer-Schaefer, H.-G.; Grigulewitsch, W.; et al. *Functional Safety of Machine Controls: Application of EN ISO 13849*; BGIA Report 2/2008e; German Social Accident Insurance (DGUV): Berlin, Germany, 2009.
85. Dindorf, R.; Wos, P. Energy efficiency of the pressure shock damper in the hydraulic lifting and leveling module. *Energies* **2022**, *15*, 4097. [CrossRef]
86. Dindorf, R.; Takosoglu, J.; Wos, P. Review of hydro-pneumatic accumulator models for the study of the energy efficiency of hydraulic systems. *Energies* **2023**, *16*, 6472. [CrossRef]
87. Dindorf, R.; Takosoglu, J.; Wos, P. *A Flexible Mechanism for Compensating Impact Loads on the Brick Gripper of an Industrial Bricklaying Robot*; Patent Application P.442477; Kielce University of Technology: Kielce, Poland, 2023.
88. *RobotStudio Operating Manual*; ABB AB Robotics Products: Västerås, Sweden, 2010.
89. *RAPID Technical Reference Manual Overview*; ABB AB Robotics Products: Västerås, Sweden, 2024.
90. Neto, P. *A Guide for ABB RobotStudio*; University of Coimbra: Coimbra, Portugal, 2014.
91. Dindorf, R.; Takosoglu, J.; Wos, P.; Chłopek, L. *Robotic Bricklaying System*; Research Reports; Kielce University of Technology: Kielce, Poland, 2022. (In Polish)
92. Follini, C.; Magnago, V.; Freitag, K.; Terzer, M.; Marcher, C.; Riedl, M.; Giusti, A.; Matt, D.T. BIM-Integrated collaborative robotics for application in building construction and maintenance. *Robotics* **2021**, *10*, 2. [CrossRef]
93. Gomes, A.M.; Azevedo, G.; Sampaio, A.Z.; Lite, A.S. BIM in Structural Project: Interoperability Analyses and Data Management. *Appl. Sci.* **2022**, *12*, 8814. [CrossRef]
94. Kynn, V. *AutoDesk Revit 2025 for Beginners*; Tektime: Montefranco, Italy, 2025.
95. Experience the Power of the World's Best BIM Viewer. Available online: https://www.dalux.com/en-gb/ (accessed on 29 January 2026).
96. Wos, P. *Robotic Bricklaying System; User Manual*; Kielce University of Technology: Kielce, Poland, 2022. (In Polish)
97. Wos, P.; Dindorf, R. Develop and implement a masonry algorithm control in a bricklaying robot. *AIP Conf. Proc.* **2023**, *2949*, 020027. [CrossRef]
98. Dindorf, R.; Chlopek, L. Impedance modeling pressure shock absorber in a hydraulic lifting system. *AIP Conf. Proc.* **2026**, *3364*, 020009.
99. Gajownik, R.; Sieczkowski, J. *Konstrukcje Murowe*; Instytut Techniki Budowlanej: Warszawa, Poland, 2023.
100. *PN-B-10110:2024-11*; Tynki Gipsowe Wykonywane Mechanicznie—Zasady Wykonywania i Wymagania Techniczne. PKN: Warszawa, Poland, 2024.
101. *Catalogue TZKNBK IV, Masonry Works*; KOPRINET Sp.z o.o.: Koszalin, Poland, 2023.
102. *ISO 10218-1:2025*; Robots for Industrial Environments—Safety Requirements—Part 1: Robots. ISO: Geneva, Switzerland, 2025. Available online: https://www.iso.org/standard/73933.html (accessed on 18 June 2025).
103. *ISO 10218-2:2025*; Robots for Industrial Environments—Safety Requirements—Part 2: Robot Systems and System Integration. ISO: Geneva, Switzerland, 2025. Available online: https://www.iso.org/standard/73934.html (accessed on 18 June 2025).
104. Nnaji, C.; Gambatese, J.; Okpala, I. *Protocol for Assessing Human Robot Interaction Safety Risks*; The University of Alabama: Tuscaloosa, AL, USA; Oregon State University: Oregon, AL, USA, 2021.
105. Roadmap for the Implementation of the BIM Methodology in Public Procurement. In *Brochure: Digitalisation of the Construction Planning in Poland*; Final report; PwC: Warszawa, Poland, 2020.

106. Borkowski, A.S.; Buniewicz, G. A critical review of the implementation of building information modelling (BIM) in construction processes in Poland: Deep insights. *Acta Sci. Pol. Arch.* **2025**, *24*, 70–91.
107. Tawfik, R.; Ucmaz, E.E. Cost efficiency: A comparison between labors and robotics in bricklaying masonry wall construction. In *Construction & Robotics, Research Driven Project*; Brell-Cokcan, S., Adams, T., Eds.; RTWH: Aachen, Germany, 2024.

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