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ORIGINAL PAPER

BRIX: an autonomous system for brick wall construction

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Abstract

A major challenge within construction robotics lies in deploying robots for building tasks directly on construction sites. Recent years have seen a surge in innovative solutions, particularly focused on creating mechanical bricklayer to automate wall construction as much as possible. However, most of these solutions involve the use of heavy industrial robots and complex systems that are difficult to calibrate and program. In this paper, the authors introduce a prototype of an automated, lightweight system for brick wall construction that is straightforward to calibrate and program. To validate the proposed approach, a full-scale demonstrator along with its control logic is presented. Experimental results, displayed at a prominent industry expo, demonstrate the viability of the proposed system. Additionally, the system was evaluated using the Construction Automation and Robotics for Sustainability Assessment Method (CARSAM), which provides a structured approach to examine the environmental, social, technological, and economic dimensions of sustainability in the context of advanced construction technologies. By applying this method, stakeholders can better understand the broader implications of integrating such technologies into construction practices, guiding more informed decisions towards sustainable development.

Keywords On-site robotics · Autonomous vehicle · Bricklaying · Algorithmic design

1 Introduction, literature review

Among various construction activities, masonry has been recognized as a prime candidate for automation due to its repetitive and almost deterministic nature, involving the placement of identical blocks in a similar manner. Furthermore, particularly when dealing with heavy blocks, masonry represents one of the most hazardous construction activities. For over 150 years, research groups worldwide have been endeavoring to craft innovative solutions for executing such building tasks. Bock and Linner (2015), Michele Ambrosino wrote extensively about the history of automation in bricklaying, starting from the first patents, proclaimed as early as 1875 by C. Franke and again in 1904 by Thomson (1904), marking the initial forays into automation. These early attempts were purely mechanical and lacked any capacity to sense or interact with their surroundings, mechanically applying mortar and placing a brick at set intervals. Despite these efforts, they failed to progress beyond the demonstration phase or achieve commercial viability. Entering the late 1980s and early 1990s, the industry began witnessing endeavors centered around robotic arms. Contrary to their purely mechanical predecessors, these newer machines incorporated an information processing unit. Employing high-degree-of-freedom robotic arms equipped with sensors and control systems, these machines were designed to "feel" the construction environment and interact with blocks. However, like earlier efforts, these too did not surpass the level of technical descriptions or prototypes, with no significant advancement thereafter. Over time, as masonry dwindled in significance as a construction technology in the developed world, so did the interest in its automation. The SAM100, a commercial machine by Construction Robotics since 2015, offers bricklaying automation for large, straight building facades (Madsen 2019). This device utilizes a standard industrial manipulator with a gripper

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mounted on a sizable mobile base, where bricks are stored and supplied to the robotic arm with mortar via a conveyor belt and mortar dispenser. Its limitation, however, lies in the requirement for a structured environment due to its movement on rails, and its capacity limited to small-sized bricks due to the nature of the industrial rigid arm. Another commercial endeavor, Hadrian X by Fastbrick Robotics (Nyamsuren 2022; Johansson 2023; James 2020), consists of a large truck equipped with a telescopic robotic arm and a conveyor belt to feed blocks to the arm's tip. Thus far, this robot has only been trialed for constructing low-rise detached houses, with its adaptability to high-rise buildings and dense urban settings remaining questionable. Further advanced prototypes in this field include DimRob (Dindorf and Woś 2022; Bonwetsch 2015; Helm et al. 2012; Dörfler et al. 2016), In Situ Fabricator (Helm et al. 2014; Buchli et al. 2018; Graser et al. 2020; Dörfler 2018), Automated Brick Laying Robot (ABLR) (Automated Brick Laying Robot [ABLR] 2024), and a crane in combination with a lightweight manipulator (Ambrosino et al. 2023). To the best of the authors' knowledge, up to this point, these systems have only managed to secure a minor role in the market, without being particularly disruptive. The SAM100—described by its creators as "the first commercially available system of its kind for onsite masonry construction"—is probably the only system that has demonstrated a significant increase in productivity over almost ten years at a commercial scale (Madsen 2019) (Fig. 1).

The limited success of automated robotic bricklaying systems in general can be attributed to several factors beyond their design for highly structured and constrained environments:

- **High initial costs**: the investment required for robotic systems is often substantial. The cost of purchasing and maintaining these robots can be prohibitive for many construction companies, particularly small to medium-sized enterprises that operate with tighter budgets.
- **Complexity of implementation**: integrating robotic systems into existing workflows can be complex and disruptive. Training staff to operate these systems, adjusting current processes to accommodate new technology, and troubleshooting initial setup issues require time and resources that many construction sites cannot afford.
- **Technical limitations**: while robotic systems are highly effective under controlled conditions, they may struggle with the variable and unpredictable nature of real-world construction sites. Issues such as dealing with different types of bricks, varying mortar conditions, and unanticipated structural anomalies can hinder their effectiveness.
- **Resistance to technological change**: there is often resistance within industries to adopt new technologies, particularly from workers who may feel that their jobs are threatened. This cultural resistance can slow down or even prevent the adoption of new technologies like robotic bricklayers.

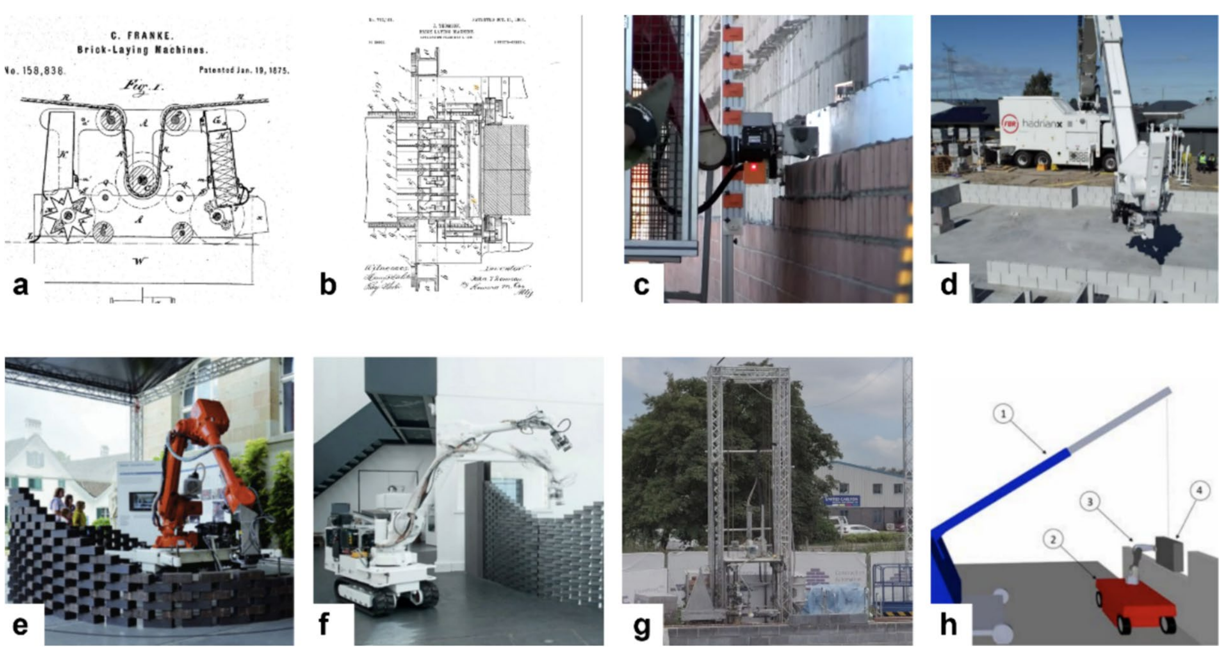


Fig. 1 Principal innovations in bricklaying machines, from 1875 to 2023: **a** patent by C. Franke; **b** patent by J. Thomson; **c** SAM100; **d** Hadrian X; **e** DimRob; **f** in situ fabricator; **g** automated brick laying robot (ABLR); **h** crane + lightweight manipulator

- **Regulatory and safety concerns**: in some regions, the use of robotic systems in construction must comply with stringent safety and labor regulations. Meeting these regulatory standards can add an additional layer of complexity and cost that discourages the adoption of these technologies.
- **Lack of proven ROI**: the return on investment (ROI) for robotic systems can be unclear or unproven to potential adopters. Companies may be hesitant to invest in technology without clear evidence that it will lead to cost savings or productivity gains in the long term.

The robotic system for brick wall construction proposed by the authors in this paper is lightweight, flexible, all electric with batteries, and autonomous, capable of navigating unstructured environments (Fig. 2), aiming to address some of the primary limitations encountered in earlier designs.

Considering the outlined challenges that have hindered the adoption of previous robotic bricklaying systems, the new BRIX system has been designed to address these specific issues effectively:

- **Lightweight**: the use of a lightweight solution, considering that the BRIX system has a total weight of 650 kg, represents an advantage in the construction sector, considering the opportunity to easily deploy the system in the work environment and to be able to operate in multiple scenarios, without an increase in complexity and cost for support infrastructures. Although there is no complete commercial information on the reference solutions identified, they are complex and heavy machines, such as the truck with robotic arm Hadrian X and the tracked solutions dimRob, and In Situ Fabricator. In the last two system mentioned, the robotic arms installed are of an industrial, non-collaborative type, with weights in themselves exceeding 450 kg, therefore, excluding the vehicle, the mechanical supports and the command-and-control electronics.
- **Reduced cost**: the BRIX system incorporates cost-effective technologies, such as off-the-shelf components. This design allows scalability based on site-specific needs, from the size of the mobile platform to the dimensions and payload capacity of the robotic arm. By lowering both the initial investment and ongoing maintenance expenses, BRIX becomes more accessible to a broader array of construction companies. In any case, the system still represents a high investment cost for small to medium-sized companies.
- **Simplified integration**: the BRIX system is designed for easy integration with a plug-and-play setup that requires minimal configuration, facilitating seamless adoption into existing construction processes with little disruption and minimal training required. It features an all-electric design, from the rover to the gripper, which enhances its portability and operation. The system can be controlled either through a joystick or an autonomous driving system, making it highly user-friendly and adaptable to various site conditions.
- **Advanced adaptability**: another challenge proposed with the BRIX system is to perform navigation and operations in an environment that the robot itself progressively builds, thus excluding navigation based completely on a pre-acquired map, but acting in exploratory mode (Palmieri and Arras 2014) to ensure that the planner of routes adapts in real time to changes in the work environment. Unlike its predecessors, BRIX features advanced sensors and AI that adapt to a variety of environmental conditions. This flexibility allows it to perform well in the less controlled environments typical of most construction sites.
- **Enhanced collaboration features**: the BRIX system is specifically engineered to foster a collaborative environment where robots and human workers operate in tandem. This technology is designed to support, not replace, human labor, significantly reducing potential resistance from the workforce. Both the rover and the robot are col-

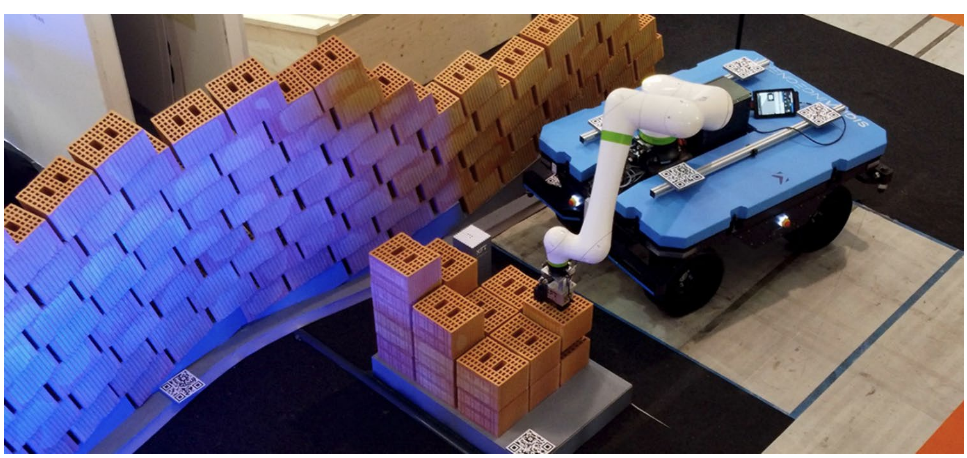


Fig. 2 Brix: a prototype of an on-site robotic manufacturing system that integrates autonomous vehicles, robotic bricklaying, and algorithmic programming

laborative, meaning they are built to work alongside construction workers, who play a crucial role in monitoring progress and ensuring everything runs smoothly. This integration is further enhanced using augmented reality to define safety zones and provide supervisory oversight, allowing for a seamless incorporation into existing practices (Fig. 3).

- **Compliance with regulations**: the design of BRIX takes into account regulatory requirements across different states, incorporating safety features that comply with EU and extra-EU standards, thus easing regulatory barriers for adoption.
- **Demonstrated ROI**: the developers of BRIX have conducted extensive field tests to provide data on productivity improvements and cost savings, offering potential buyers a solid basis for calculating the return on investment.
- **Robust support and training**: BRIX comes with comprehensive support and training resources, ensuring that the transition to its use is as smooth as possible and that any issues can be quickly addressed.

By directly addressing the limitations of earlier systems, BRIX aims to offer a solution that could significantly enhance productivity and efficiency in the construction industry.

2 The BRIX system: methods and research approaches

In this section, the BRIX system is described along with the selected methods and approaches used for the development of its hardware and software architecture. From the autonomous driving vehicle to the brick pick-and-place application.

The vehicle is equipped with four-wheel drive and steering, airless tires, high-efficiency rechargeable lithium batteries, industrial-grade control electronics and safety sensors necessary to guarantee compliance with current regulations in terms of machinery safety. Furthermore, it is equipped with a control system compatible with manual remote operation and autonomous navigation, making it in all respects an AMR (Autonomous Mobile Robot).

The choice of a system equipped with four independent driving and steering wheels is dictated by the need to guarantee any type of movement to the Rover. We start from the more conventional four-wheel-steering capability, then move on to movement with parallel wheels, useful for precise lateral or diagonal translational movements, up to rotation on the spot to change direction of motion with zero turning radius (Fig. 4). Compared to a tracked vehicle or one equipped with a differential drive, therefore, the execution of movements to reach the operational targets on the construction site is more accurate, also allowing to better orient the direction of the vehicle, and, therefore, of the robotic arm, to optimize its construction operations. More specifically, consider managing the positioning in a specific point of the construction area, characterized by obstacles such as pillars, already built walls or plants, and the need to orient the arm to create a last section of wall that is difficult achievement. The different movement modes can be combined sequentially to reach the desired target (position and orientation) (Fig. 5).

In the second half of 2023, in view of the creation of the BRIX system and the demonstration at the prestigious SAIE fair in Bari dedicated to the world of construction, the authors integrated a Fanuc collaborative robotic arm with its controller on the Rover, in order to create a complete,

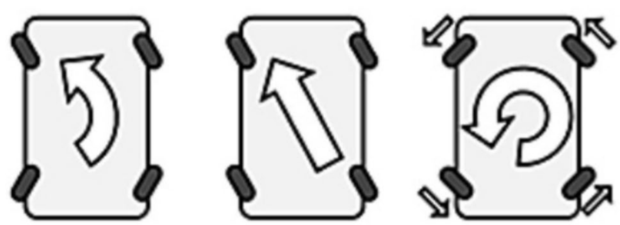


Fig. 4 Diagrams of the Rover's different movement modes

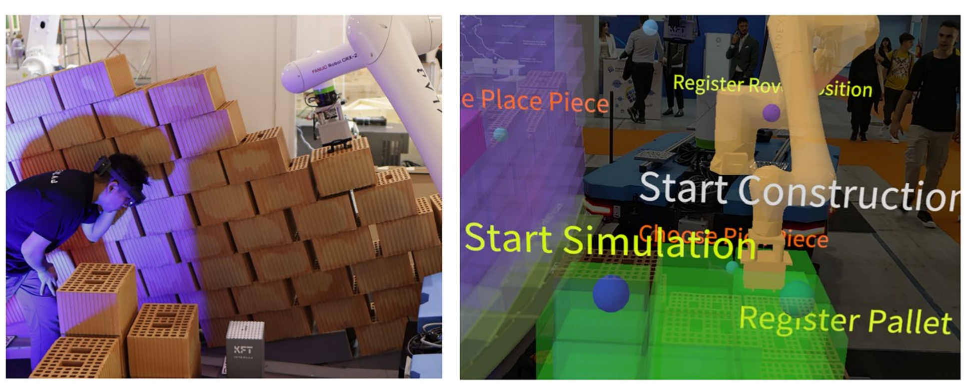


Fig. 3 Collaborative integration at work: the BRIX system, featuring a rover and a robotic arm, operates alongside construction workers, who utilize augmented reality (Holo2) for enhanced supervision and safety management, exemplifying the seamless blend of human expertise and robotic efficiency

Fig. 5 Featuring four-wheel drive, airless tires, and autonomous capabilities, this AMR complies with safety standards and supports both manual and autonomous navigation

versatile and cooperating robotic platform for the creation of brick structures.

The integrated system consisting of the Rover and the Fanuc arm, a collaborative CRX-25iA with a maximum payload of 30 kg and a maximum reach of 1890 mm, constitutes a work platform for the creation of complex brick structures, combining navigation functionality in complex and highly variable environments, such as those found on a construction site, with pick and place tasks using the anthropomorphic arm.

Thanks to the creation of a hardware and software infrastructure with user friendly interfaces, suitable for use by operators in the sector with average experience in these technologies, the objective of the robotic platform is to make the processes in the construction sector more efficient and safer, with a positive impact first of all on a social level, with a reduction in heavy work thanks to the adoption of this type of technical solution. Although the construction sector has been experiencing a significant labor shortage in recent years, the aim is rather to lead to the development of skills, shifting the work target of operators, while improving safety standards, thus contributing to a broader socio-economic progress in a sustainable manner.

The integrated system, also introducing cutting-edge robotic solutions that favor sustainability and environmental responsibility, intends to significantly reduce the environmental footprint associated with the aforementioned activities, allowing for a more efficient use of resources, minimizing waste of material and optimizing the use of resources, having the possibility of acquiring, historicizing and processing data during work activities, therefore, increasingly improving performance thanks to machine learning techniques.

The Rover's navigation system is based on various sensors, chosen on the basis of technology reliability requirements, also depending on the operational scenario, and also having sensor fusion tools, designed to jointly process the information coming from the sensors with appropriate filters, ensuring better reliability of the acquired data, therefore, of the decision-making process for autonomous navigation. Specifically, the Rover installs Lidar sensors (Lidar sensors. 2024), capable of generating dynamic point clouds to map the environment a priori and in real time, and stereo-cameras (Stereo cameras. 2024), vision sensors with 3D perception, capable of detecting objects in the environment, classifying them, and determining their spatial position and direction of movement (Fig. 6).

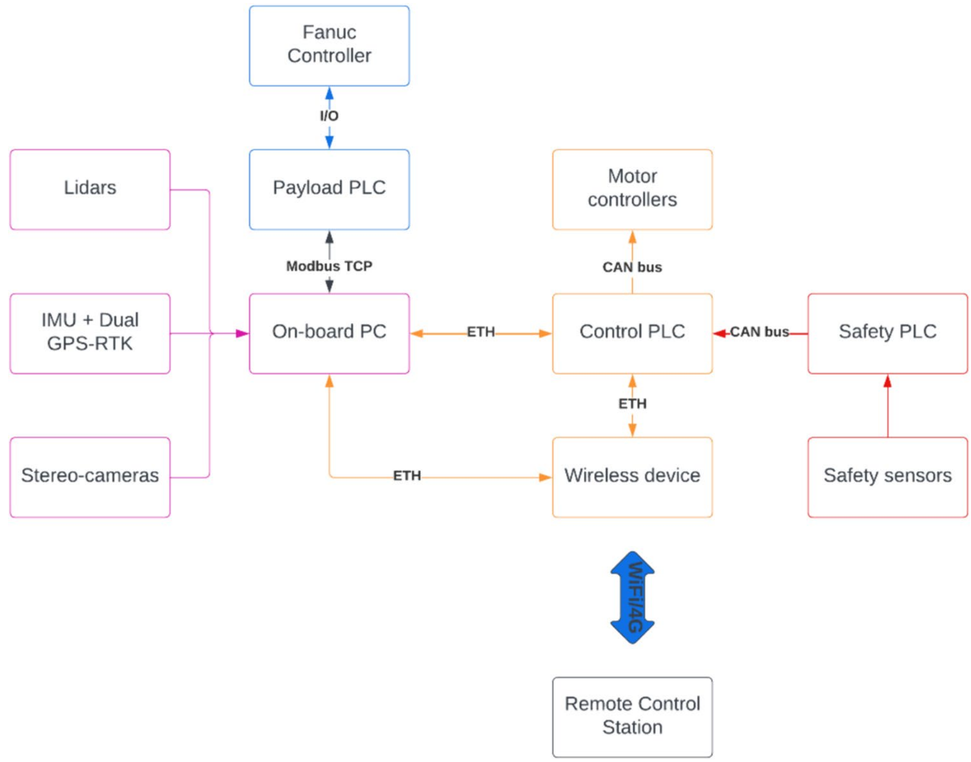
The union of the data coming from the sensors, together with the spatial localization information of the vehicle, collected and combined with appropriate filters, starting from sources, such as the wheel encoders and the differential GPS–RTK, allows to manage the navigation tasks according to the block diagram (Fig. 7).

The work environment can be mapped in advance, to determine some spatial constraints or insert references for the processes, or simply explored, the latter option being more suitable for a highly variable environment such as that of a construction site, where the presence whether or not there are walls varies from one hour to the next due to work activities.

The setting up of a work plan which, as described below, will be strictly connected or the activities of the robotic arm, then allows to pre-determine the vehicle's mission, including various additional parameters such as the speed to maintain in the various sections or the orientation of the vehicle. Navigation is, therefore, carried out thanks to planning algorithms (Alarabi et al. 2022) which, based on any pre-acquired data, the work plan, and real-time detections of obstacles during the routes, commands the vehicle's movements, monitoring its behavior and correcting it in case of deviations from what was expected.

From a mechanical point of view, the central area of the vehicle, originally open to accommodate a payload, was closed with stainless steel sheets, including a robust bracket for the installation of the arm, all sized to withstand static and dynamic loads transmitted from Fanuc to the Rover structure. For this evaluation, the most severe scenario was considered according to the datasheet of the

Fig. 6 Hardware architecture scheme



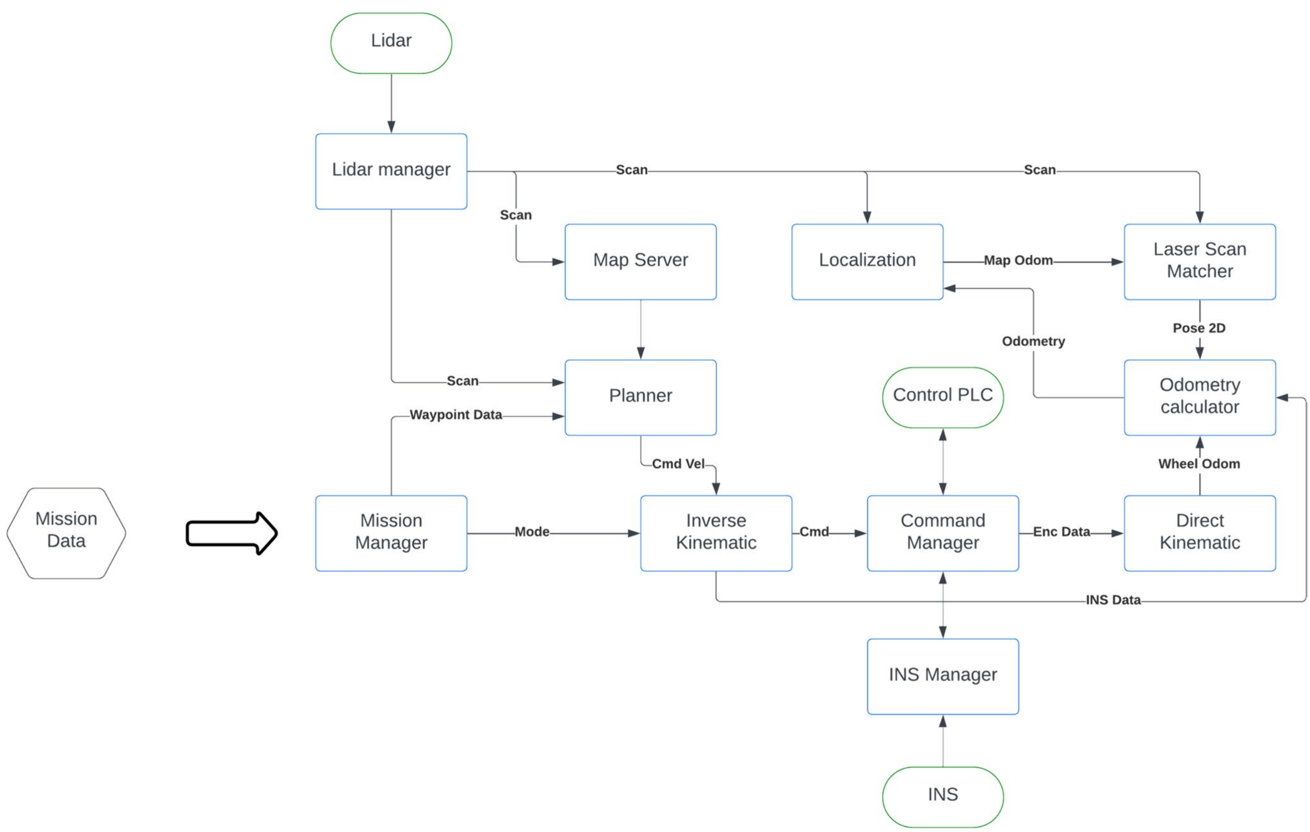


Fig. 7 Software architecture scheme

manufacturer Fanuc, i.e. in the event of a sudden stop during movement with the arm fully extended (about 1.90 m) and at full load (30 kg). This condition in fact gives rise to the maximum torque on the connection interface in the considered plane.

Another analysis performed concerns the verification of the vehicle not overturning, considering the same critical case described above, with limit state analysis: conservatively considering the vertical force not amplified by impulsive forces and/or dynamic effects, the comparison was carried out between the resultant of the overturning and stabilizing moments. In both cases, the reference pole is the contact point of the wheels (processing side), based on the plane considered. The safety margin, although a few percentage points lower than unity, gave a positive result in the verification.

The robot controller was instead installed mechanically using the holes already prepared on the bottom of it, on one of the stainless-steel plates prepared on the vehicle.

From an electrical point of view, the provisions implemented are:

- Installation of an inverter to convert the battery voltage (48VDC) into alternating current (220VAC 50 Hz), necessary to power the Fanuc controller.
- Connection of the Fanuc controller safety to the Rover safety PLC.
- Installation of a PLC to manage communication between on-board PC and Fanuc controller.

The software integration between Rover and robotic arm sees an exchange of information via Modbus TCP protocol between the vehicle's on-board computer, also dedicated to the navigation tasks described above, and the PLC dedicated to managing the payload. The interaction involves "waypoint actions", i.e. an alternation between movement of the Rover to reach a work point and pick & place activities performed by the Fanuc robot, to pick up and position the brick to build the wall. The on-board computer then communicates bidirectionally with the Fanuc controller, activating one of the two tasks, movement of the Rover or movement of the arm, depending on the corresponding state machine.

The hardware and software implementation, as in any technological project, requires an important testing phase, as was naturally the case for BRIX, starting from analyzing the behavior of the various subsystems, Rover, robotic arm, vision system, end-effector, with testing activities performed separately by Sigma Ingegneria and Indexlab. All followed by an important joint integration and test activity to create the complete system, starting from the first tests carried out in Lucca at Sigma Ingegneria, to conclude with the latest tuning in Lecco at Indexlab—Politecnico di Milano Polo Territoriale di Lecco (Fig. 8).

A different scenario and a different preparation and setup activity characterized the setup of the demonstrator presented at the SAIE fair in Bari, considering two important critical issues such as the limited spaces of the fair and the presence of a large public, as demonstrated during the 3 days of the event, an aspect which, however, appropriately

Fig. 8 Testing the BRIX system in Lucca at Sigma Ingegneria (Left), testing in Lecco at Indexlab—Politecnico di Milano Polo Territoriale di Lecco (Right)

Fig. 9 Testing the Brix system in Bari at SAIE fair 2023

managed, allowed for an effective and impactful demonstration (Fig. 9).

Paying attention to the safety aspects of the workplace represents a key point of the BRIX project, taking care to design a system that can respond to the requirements imposed by current regulations, but also to bring added value to the work environment, improving its general conditions.

According to a Eurostat study from October 2023 (Eurostat 2023) the majority of non-fatal or fatal workplace accidents in the EU in 2021, broken down by percentage by type of activity, occur in the construction and transport and storage fields. These incidents often involve the movement of materials using equipment like forklifts, cranes, and overhead cranes, underlining the critical safety concerns in these areas (Fig. 10).

In this scenario, the use of self-driving vehicles can be safer than the traffic of forklifts or other vehicles controlled manually by an operator (e.g., forklift with driver on board), as they cannot cause damage to people or infrastructures thanks to the safety devices that are mounted on board, such as to allow collision prevention. Similarly, a collaborative robotic arm, therefore, equipped with all the features to be able to coordinate its operations in the same environment in which people move, represents a notable improvement for the safety of the working environment.

The reference standard for the safety of autonomous vehicles at European level is EN 3691–4:2023 (Industrial trucks – Safety requirements and verification 2023): this document is applicable to all unmanned industrial vehicles on board, including AGVs, AMRs, robotic forklifts and describes the methods of safely managing these vehicles, giving particular emphasis to the continuous monitoring of the work area.

The sensors act as a guarantee in this scenario, particularly the safety LiDARs mounted on the Rover, capable of

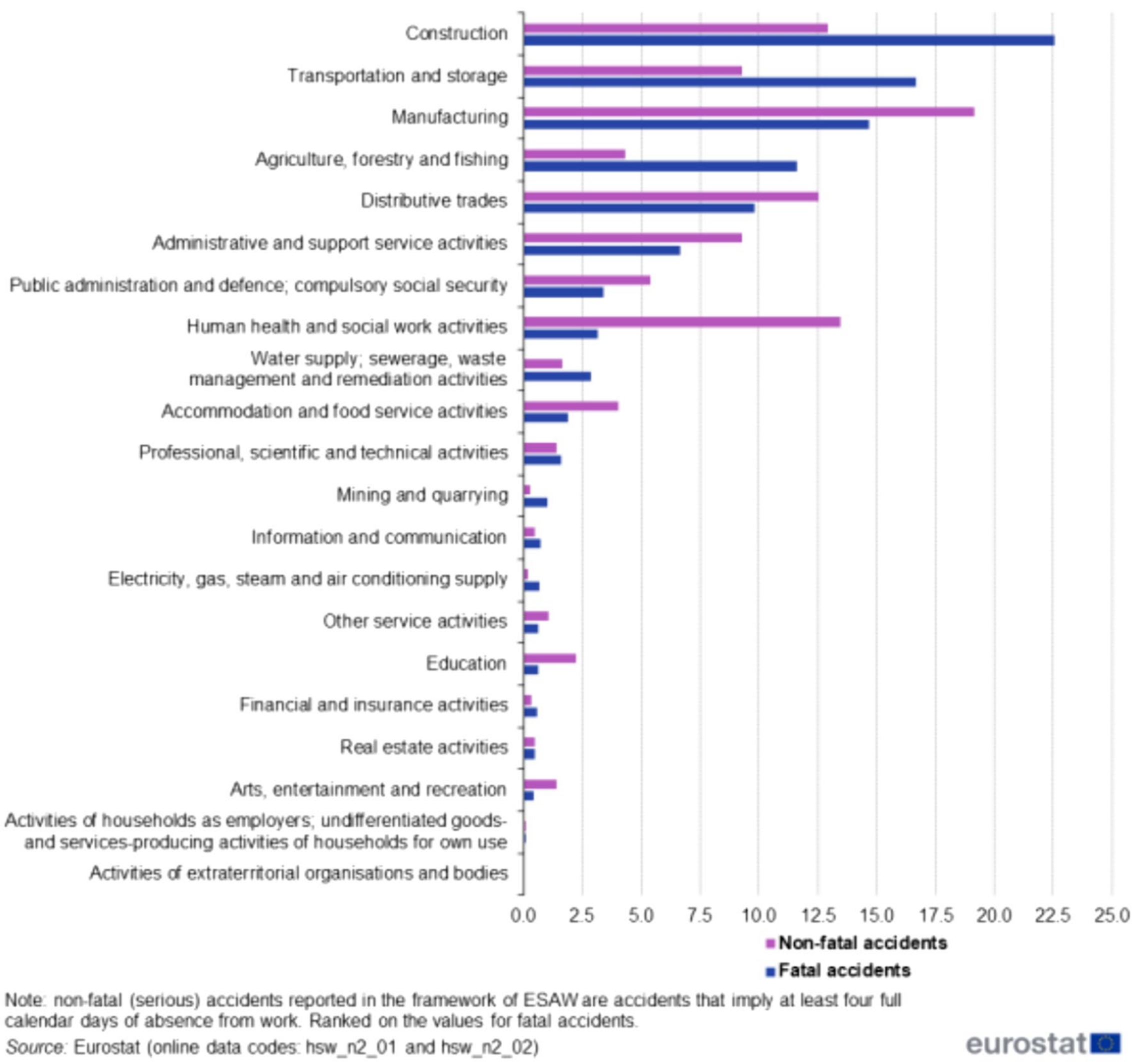


Fig. 10 Diagram showing the percentage of Fatal and non-fatal accidents at work by NACE section, EU, 2021, by Eurostat

monitoring any human presence around it or on the path of the vehicle, stopping the latter in the event of a potential collision. Through a dedicated safety PLC, they also help to determine the "safe speed", a value depending on the load and the computational time of sensors and processing units, such as to guarantee the safe stopping of the vehicle before of potential collision with someone or something. By preventing collisions of all types, AMRs create a safe working environment for people while limiting damage to infrastructure and transported materials.

From the point of view of the safety of the robotic arm, it should be underlined that, although it may seem counterintuitive, there is no such thing as a "collaborative robot", but it is the application that makes the "Collaborative Robot", as it must be appropriately designed for a task of this nature. For this area, reference is made to the ISO 10218 standard and to the technical specification ISO/TS 15066 (ISO, TS 2016): the robot and the human operator "share" the common work space, without the need for barriers, unlike what is needed for traditional industrial robots.

In short, therefore, BRIX was not only guided by technical and production aspects, but also of a more social nature, with the objectives of sharing space between robots and humans and increasing the level of safety in the workplace.

The interaction between man and machine was also demonstrated during the exhibition and demonstration of the SAIE 2023 fair in Bari, a real opportunity to showcase to industry experts and the public the advantages of deploying robotic systems to perform laborious and repetitive tasks. This allows human workers to focus their valuable time on less strenuous, more specialized, and intellectually demanding activities.

2.1 Operational configuration and work environment

The system is equipped with an easy-to-use user interface, dedicated both to programming the movement of the Rover and to setting the work program of the robotic arm. For the first aspect, the user has a simple adaptive web-based interface available, therefore, suitable for viewing on different types of devices, PCs, tablets and smartphones, so as to allow quicker and more immediate access in the last two cases. In the user interface the operator can, therefore, program the mission by defining the work points with coordinates referring to an environmental map (useful if the construction site designer has spatial references of the work area) and the actions to be performed in them, thus interacting with the program of the robotic arm and its movements. The interface also contains telemetric information on the status of the vehicle, to highlight the Rover conditions and any ongoing problems (Fig. 11).

The robotic arm also has an easy-to-access graphical programming interface, capable of setting all the necessary movements, also considering the tasks of identifying markers for calibration and interactions with the movement of the Rover, thus completing the layout of user accessibility.

Integration into construction processes, although it implies training activities for the operators, does not require previous technical or engineering training, making the necessary knowledge gap minimal. The highly adaptive system, i.e. capable of operating in unstructured, highly variable and self-calibrating environments, offers an enormous advantage for the construction company, dedicating an essential amount of time to training, without, therefore, having to have highly trained workers, specialized in the operation of complex robotic vehicles.

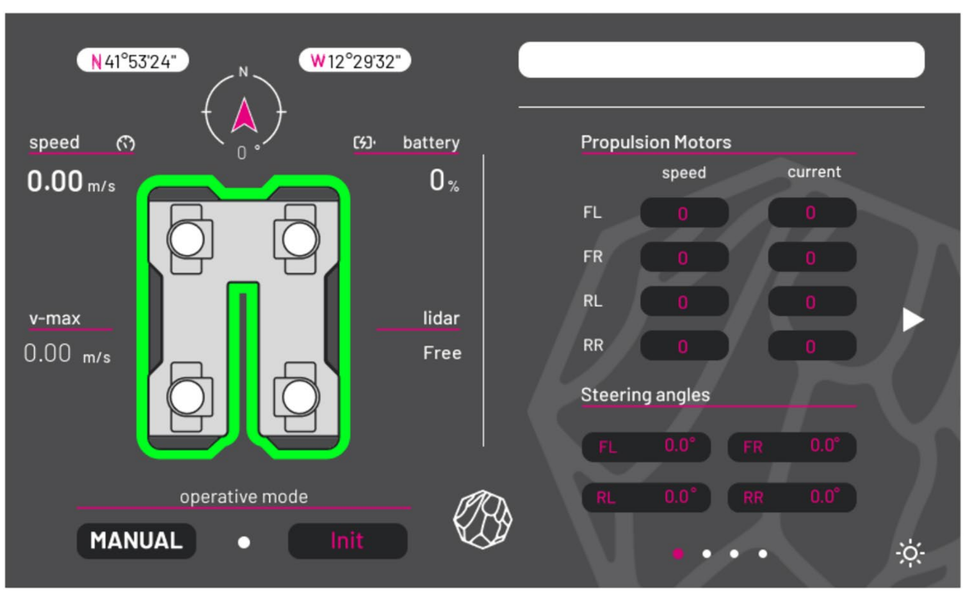


Fig. 11 Example of Rover HMI screen with telemetry

In the following section, the data described refers to one of the most complex tests of the demonstrator, where the robot constructs not straight walls, but curved walls with an inclined deposition plane. The system is programmed to erect a freeform wall utilizing dry-stacked bricks, staggered and inclined at 30°, previously arranged on a pallet in a $3 \times 3x3$ grid. The operational environment, approximately 8×3 m, is delineated by a station-based itinerary on predetermined points for the rover's positioning, simultaneously ensuring the accessibility of the gripping pallet and the brick release point by the robotic arm. The origin point, defined as point 0, establishes the succession of positions that the vehicle must reach during construction.

2.2 Robotic system components

In addition to the previously described rover, the robotic system includes:

Robot: The Fanuc CRX-25iA, a collaborative manipulator arm with a maximum load capacity of 30 kg, designed to support heavy object movement applications, such as construction bricks.
Controller: The R-30iB Mini Plus model is suited for rover mounting with dimensions of $410 \times 277 \times 370$ mm.
Gripping Device: The Schunk EGU 60-IL-M-B can apply a force of 1300 N, suitable for precise millimetric manipulation of bricks. Brick gripping can occur via clamping or extraction, i.e., applying radial force from the center outward.
Vision System: The IrVision 2D is employed for robot reorientation relative to a recognized reference system by the vision algorithm.

2.3 Programming

The system's programming is divided into two phases:

Offline Programming, remotely in a BIM environment;
Online Programming, proximate to the processing;

The offline programming phase occurs within a BIM software, constructing an algorithm according to a sequence of operations that sequentially manages the number of bricks to operate on in the *n* station to build each wall portion. This includes a series of movements for each brick as follows:

- linear approach to the gripping point;
- linear positioning of the robot on the gripping point;
- gripper tightening;
- linear withdrawal from the gripping point;
- joint movement towards the release point;
- linear approach to the release point;
- linear positioning of the robot on the release point;
- gripper opening;
- withdrawal from the release point.

Following offline programming completion and program transfer to the controller, the next phase continues with the rover's positioning at the first established points and the integration of the vision system and communication logic between the rover and robot (Fig. 12).

Upon reaching the *n* station, the rover sends a digital signal to the robot, unlocking the execution of subsequent operations. To re-orient its movements by correcting potential rover positioning errors, the execution of commands defined in offline programming is permitted only following validation by the vision algorithm. This procedure involves positioning the camera at a height allowing targeting towards a specific marker, constituted by a recognized point grid by the algorithm, located near a pallet corner, redefining the shared reference system by the robot, pallet, and wall, previously defined during offline programming. Once the marker position and thus the correction of the subsequent point sequence are validated, the robot executes the programmed instructions for that wall portion. Upon completion, it sends a digital signal to the rover, which moves towards the next station.

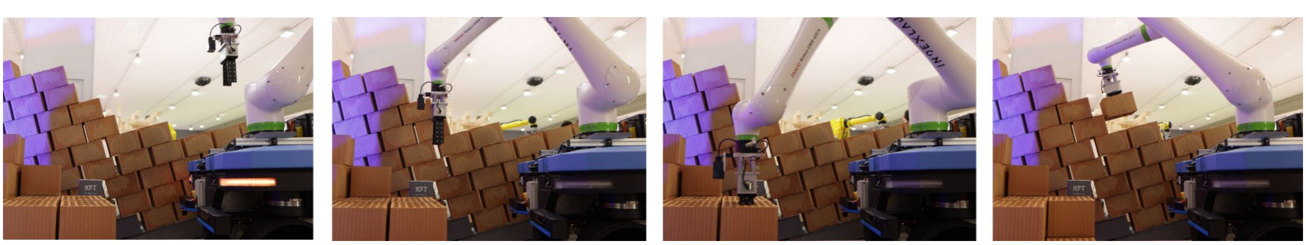


Fig. 12 Operation sequences of BRIX constructing a wall in Bari at SAIE fair 2023

3 Results—evaluated using the CARSAM framework

BRIX main aim is to advance modern construction methodologies through automation. A way to qualitatively evaluate its impact can be proposed taking advance of the Construction Automation and Robotics for Sustainability Assessment Method (CARSAM), initially conceptualized by M. Pan et al. (2018) in the Journal of Cleaner Production (Pan 2018). This application enables the previously theoretical CARSAM to assess construction automation systems across social, environmental, economic, and technological dimensions. The validity of this approach is underscored in Leder et al.'s discussion about performance metrics for automation in construction, where they recognize the theoretical value of CARSAM. Although it had not been practically applied until now, its potential to offer a novel methodology for quantifying the real-world impacts of construction automation has been acknowledged. To the best of the authors' knowledge, this study represents its inaugural application in a practical context, marking a transition from theory to practice.

The implementation of the CARSAM starts from the assessment of the 75 proposed indicators using a qualitative approach. Each indicator is rated as negative, neutral, or positive, represented by the colors red, yellow, and green, respectively. These evaluations, derived from a consensus among the BRIX team, form the basis for the assessment's visual representation. A dedicated algorithm utilizes these collective scores to create a visual diagram that not only displays the immediate data but also adjusts the representation to illustrate the cumulative impact across broader categories. This visualization effectively bridges detailed assessments to provide a comprehensive view of BRIX's influence on construction practices from different perspectives, while illustrating the practical utility of the CARSAM framework in assessing the sustainability impacts of construction automation technologies.

3.1 Social impact

From a social perspective, BRIX demonstrates its most significant benefits, particularly in relation to employees at the project level. It enhances occupational health and safety, boosts job satisfaction, and fosters workforce development. However, fewer advantages are observed at the corporate level. It is important to note a significant drawback concerning governmental approval, which remains a challenge.

3.2 Environmental impact

In terms of environmental impact, BRIX's effects on material consumption, as well as greenhouse gas emissions, and the consumption of land, air, and water resources are considered neutral when compared to human labor. This suggests that while BRIX does not significantly reduce resource use or emissions beyond current human levels, it also does not exacerbate them. The environmental goals of compliance and achievement of set objectives are successfully met with the implementation of BRIX.

3.3 Economic impact

The long-term economic impacts and both direct and indirect economic benefits are highlighted. Nonetheless, high direct and indirect costs associated with the implementation of the system persist and mostly depend by the lack of supportive market and policy frameworks to foster the adoption of such systems.

3.4 Technological impact

The assessment reveals a high degree of flexibility in the tool, with its robustness still uncertain due to the novelty of the instrument. Accessibility is clearly lacking, given the limited dissemination and the still prototype nature of the tool.

In the conducted analysis, the use of BRIX has generally shown a positive influence on all the examined macro-categories. However, significant exceptions were found in the areas concerning immediate costs and technological accessibility. These limitations are attributable, respectively, to the lack of financial support policies for companies adopting such technologies and to the still prototypical nature of the tool analyzed.

In Table 1, a list of all the indicators with the identified scores is presented, while Fig. 13 shows the overall diagram.

4 Discussion

As can be seen from the description of the system and the design and implementation activities, the challenges in the development of the Brix project were multiple, starting with the identification of a structural layout capable of guaranteeing resistance and stability to the development of navigation algorithms to manage movements between two waypoints in an optimal way, considering the possible presence of obstacles. Making the system robust meant evaluating software strategies aimed at implementing actions to correct or at least consider deviations from the optimal movement, both as regards the Rover and for the pick & place actions of the robotic arm. The result shown to the public at the fair and digitally on social media and company websites is, therefore, the result of a synergy between all the partners, to create an efficient but also

Table 1 List of all indicators

	SOCIAL
	SO.0 - Reduction of injuries and fatalities
	SO.1 - Reduction of heavy works
	SO.2 - Impacts on physical working condition
	SO.3 - Reduction of working hours
	SO.4 - Improved job satisfaction
	SO.5 - Impacts on job security and welfare
	SO.6 - Providing additional capacity development
	SO.7 - Improved job attractiveness
	SO.8 - Improved client and end-user satisfaction
	SO.9 - Impacts on upstream and downstream tasks in the project
	SO.10 - Impacts on building or unit price
	SO.11 - Reduction of project disturbance to site neighbors
	SO.12 - Reduction of environmental impacts of the project to the local community
	SO.13 - Improved continuity and stability of the employment
	SO.14 - Promoting the culture of innovation
	SO.15 - Impacts on enterprise cohesion
	SO.16 - Responsibility and accountability issues
	SO.17 - Impacts on maintaining the long-term partner relationship
	SO.18 - Alleviating skilled labor shortage problems
	SO.19 - Stimulating technological innovation
	SO.20 - Reforming labor market
	SO.21 - Impacts on obtaining the governmental approval of construction works
	SO.22 - Provision of high-tech job opportunities
	ENVIRONMENTAL
	EN.0 - Raw material consumption saving
	EN.1 - Material recycling
	EN.2 - C&D waste reduction
	EN.3 - Energy saving in process refinement
	EN.4 - Energy consumption for operation
	EN.5 - GHG emissions saving in process refinement
	EN.6 - GHG emissions in operation
	EN.7 - Site land consumption saving
	EN.8 - Land saving in waste landfilling
	EN.9 - Impact on urban mining
	EN.10 - Space requirement for operation and storage
	EN.11 - Air pollution reduction
	EN.12 - Noise emission reduction
	EN.13 - Water consumption saving
	EN.14 - Water recycling
	EN.15 - Water pollution reduction
	EN.16 - Impacts on the achievement of environmental goals
	EN.17 - Compliance with environmental legislation
	EN.18 - Compliance with environmental policies
	EN.19 - Compliance with environmental standards

Table 1 (continued)

	ECONOMIC
	EC.0 - Saving in labor cost
	EC.1 - Saving in resource cost
	EC.2 - Saving in cost for waste management
	EC.3 - Saving in time
	EC.4 - Saving in rework reduction
	EC.5 - Improved quality of works
	EC.6 - Incentives for innovation
	EC.7 - Capital cost (Acquisition cost)
	EC.8 - Operation cost
	EC.9 - Maintenance cost
	EC.10 - Cost for training workforce
	EC.11 - Cost for consulting professionals
	EC.12 - Payback period
	EC.13 - Return on investment
	EC.14 - Impacts on trading opportunities
	EC.15 - Impacts on company's reputation
	EC.16 - Impacts on competitiveness
	TECHNOLOGICAL
	TE.0 - Technology popularity and reputation
	TE.1 - Technology readiness level
	TE.2 - Mean time to repair
	TE.3 - Mean time between failures
	TE.4 - Friendliness of interface with manual workers
	TE.5 - Interoperability with other technologies
	TE.6 - Size, weight, power and mobility
	TE.7 - Reusability in different scenarios
	TE.8 - Flexibility of function
	TE.9 - The ability to future upgrades
	TE.10 - Technology suppliers
	TE.11 - Local availability of servicing resources
	TE.12 - Local availability of machine components
	TE.13 - Public awareness level
	TE.14 - Availability of supportive policies

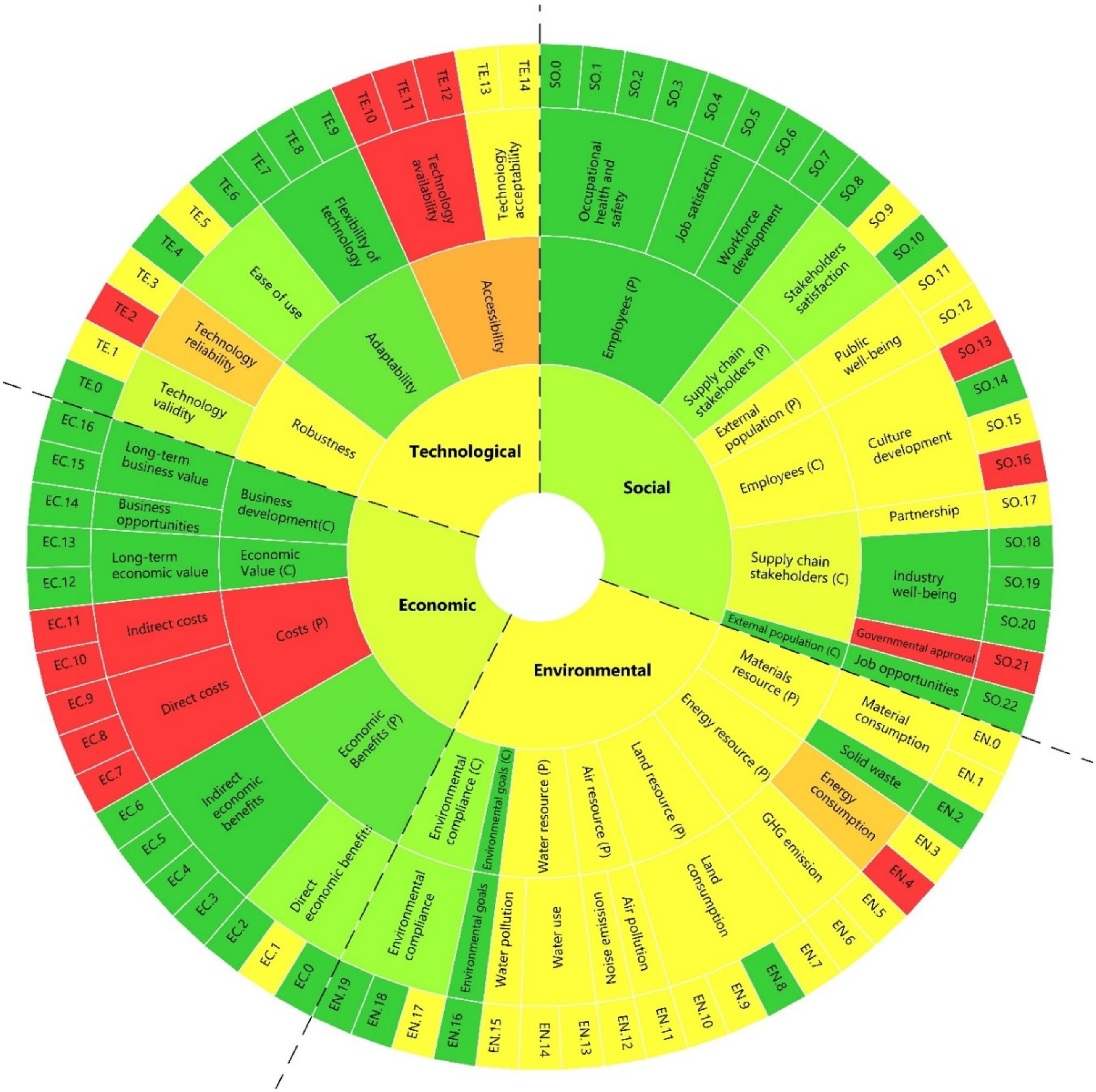


Fig. 13 Construction Automation and Robotics for Sustainability Assessment Method—CARSAM—provides a structured approach to examine the environmental, social, technological, and economic dimensions of sustainability in the context of advanced construction technologies. By applying this method, stakeholders can better understand the broader implications of integrating such technologies into construction practices, guiding more informed decisions towards sustainable development

commercially interesting system, with the ultimate aim of opening a market that has enormous potential for this technology. In addition, the previous chapter examined the multifaceted impacts of the BRIX system using the Construction Automation and Robotics for Sustainability Assessment Method (CARSAM). The author's findings indicate that BRIX offers substantial social benefits at the project level by improving occupational health and safety. Economically, BRIX shows potential for long-term benefits, both direct and indirect. However, the high costs associated with its implementation underscore a need for supportive market and policy frameworks that could ease and encourage its integration into the industry.

5 Conclusions and future work

As part of the advanced development phase, the authors are ready to evolve with the creation of even more sophisticated and efficient systems. The Rover was created to operate in an outdoor environment; therefore, with uneven pavements and in adverse weather conditions, an aspect that requires further fine-tuning of the perception and calculation modules of the optimal routes of the navigation system, to make the AMR completely effective in complex and highly variable scenarios (Yu et al. 2019). Another goal is to minimize operating times, decrease waiting periods and reduce resource consumption by improving work efficiency. It is planned to exploit the innovative Reinforced Learning techniques (Lee and Yusuf 2022), such as to allow the robots to learn to navigate according to the outcomes of the entire production process, ultimately aiming to obtain Continuous Learning capabilities, for continuous adaptation to variability operational. By integrating AI capabilities and insights gained from collected data (Tish et al. 2020), the aim is to improve decision-making processes and streamline operations, ultimately achieving greater productivity and better use of resources within the system. Spreading this technology to a greater variety of end-users ultimately requires modifications to the Rover platform, reducing the size of the vehicle to facilitate access to smaller work areas and integrating a linear vertical movement system to increase the operating range in altitude up to 3 m, covering a greater number of operational cases.

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