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Disrupting Buildings

Digitalisation and the Transformation of Deep Renovation

Edited by
Theo Lynn · Pierangelo Rosati
Mohamad Kassem · Stelios Krinidis
Jennifer Kennedy

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ISSN 2662-1282 ISSN 2662-1290 (electronic)
Palgrave Studies in Digital Business & Enabling Technologies
ISBN 978-3-031-32308-9 ISBN 978-3-031-32309-6 (eBook)
https://doi.org/10.1007/978-3-031-32309-6

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This Palgrave Macmillan imprint is published by the registered company Springer Nature Switzerland AG.
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

ACKNOWLEDGEMENTS

This book was partially funded by the European Union's Horizon 2020 Research and Innovation Programme through the RINNO project (https://rinno-h2020.eu/) under Grant Agreement 892071, and the Irish Institute of Digital Business.

BOOK DESCRIPTION

The world's extant building stock accounts for a significant portion of worldwide energy consumption and greenhouse gas emissions. In 2020, buildings and construction accounted for 36% of global final energy consumption and 37% of energy-related CO_2 emissions. The European Union (EU) estimates that up to 75% of the EU's existing building stock has poor energy performance, 85–95% of which will still be in use in 2050.

To meet the goals of the Paris Agreement on Climate Change will require a transformation of construction processes and deep renovation of the extant building stock. The World Economic Forum, World Business Council for Sustainable Development, and the European Commission are amongst the many global organisations that recognise the important role ICTs can play in construction, renovation, and maintenance, as well as supporting the incentivisation and financing of deep renovation. Technologies such as sensors, big data analytics and machine learning, building information modelling (BIM), digital twinning, simulation, robots, cobots and unmanned autonomous vehicles (UAVs), additive manufacturing, smart contracts, and the Internet of Things are transforming the deep renovation process, improving sustainability performance, and developing new services and markets.

This book defines a deep renovation digital ecosystem for the twenty-first century, providing a state-of-the art review of current literature, suggesting avenues for new research, and offering perspectives from business, technology, and industry.

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ABBREVIATIONS

4M	Mapping, Modelling, Making and Monitoring
API	Application Programming Interface
AR	Augmented Reality
AWS	Amazon Web Services
B2B	Business-to-Business
B2B2C	Business-to-Business-to-Consumer
B2C	Business-to-Consumer
BACS	Building Automation and Control Systems
BEMS	Building Energy Management Systems
BIM	Building Information Modelling
CIB	International Council for Research and Innovation in Building and Construction
CO_2	Carbon Dioxide
CSP	Cloud Service Provider
EC	European Commission
EU	European Union
GDP	Gross Domestic Product
GHG	Greenhouse Gas
HVAC	Heating, Ventilation, Air Conditioning
IAAS	Infrastructure as a Service
ICT	Information and Communications Technologies
IDDS	Integrated Design and Delivery Solutions
IEEE	Institute of Electrical and Electronics Engineers
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organisation for Standardisation
ISV	Independent Software Vendor
KPI	Key Performance Indicator

CHAPTER 8

Intelligent Construction Equipment and Robotics

Alessandro Pracucci, Laura Vandi,
and SeyedReza RazaviAlavi

Abstract With recent advancement in software, hardware, and computing technologies, applications of intelligent equipment and robots (IER) are growing in the construction industry. This chapter aims to review key advantages, use cases and barriers of adopting IER in construction and renovation projects. The chapter evaluates the maturity of available IER technologies in the market and discusses the key concerns and barriers for adopting IER such as the unstructured and dynamic nature of construction sites limiting mobility and communication of IER, hazards of human-robot interactions, training and skills required for operating and collaborating with IER, and cybersecurity concerns. Finally, the chapter

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T. Lynn et al. (eds.), *Disrupting Buildings*, Palgrave Studies in
Digital Business & Enabling Technologies,
https://doi.org/10.1007/978-3-031-32309-6_8

proposes a framework for implementing IER that helps in their benefits by defining relevant metrics while considering their pitfalls in terms of quality, safety, time, and cost. This framework assists practitioners in decision-making for adopting IER in their construction operation.

Keywords Robotics • Construction • Safety • Monitoring • Quality control • Assessment framework

8.1 KEY DEFINITIONS AND CONCEPTS

Table 8.1 provides a summary of key definitions and concepts related to the use of intelligent construction equipment and robotics in the construction industry.

Table 8.1 Key definitions and concepts

Construction Automation and Robotics (CAR)	A field of research and development focused on automating construction processes; construction automation deals with applying the principles of industrial automation to the construction sector (Saidi et al., 2016).
Single Task Construction Robots	Robots or automated devices that are developed primarily for performing a specific task on the construction site (Hu et al., 2020).
Integrated Robotised Construction Sites	Construction sites in which multiple robots/machines collaborate to build an entire structure (Saidi et al., 2016).
Teleoperation	A robot technology where a human operator controls a remote robot (Lichiardopol, 2007).
Programmable Construction Machines	A type of machine of which operator can change the activities to be accomplished within certain constraints either by selecting from a preprogrammed menu of functions or by teaching the machine a new function (Saidi et al., 2016).
Intelligent Systems	Software programs that syndicate the knowledge of experts and attempt to resolve distinct problems by imitating the reasoning processes of experts (Irani & Kamal, 2014).
Cobots	A system that amplifies or assists human skills, while performing tasks that require both the capacity of a human and the accuracy of a robot (Melo et al., 2012).
Exoskeletons	Emerging wearable technologies involved in the entire construction sector phase which allow to facilitate construction workers to lift heavy weights by reducing fatigue and site injuries and improving the work productivity (Kim et al., 2019).

(*continued*)

Table 8.1 (continued)

Robots	Devices that execute specific operations either autonomously or under an operator's direct control. The use of robots on construction sites is still very limited but the robotics production market is predicted to grow steadily over the next few years (Davila Delgado et al., 2019; European Construction Sector Observatory, 2021).
Unmanned Aerial Vehicle (UAV)	Commonly known as "drones," programmed technologies which can perform air operations reaching dangerous places for humans. Their use results in evident economic savings and environmental benefits while reducing the risk to human life (Outay et al., 2020).

8.2 INTRODUCTION

The construction industry plays a crucial role in ensuring job creation, driving economic growth, and providing solutions to address environmental, social, and economic challenges. The market value of the construction sector represents between 9% and 15% of GDP in most countries (Davila Delgado et al., 2019). Despite its huge economic importance, the construction industry is traditionally slow to change and consequently beset with inefficiencies resulting in lower productivity levels compared to other sectors (Davila Delgado et al., 2019). However, despite the complexity and fragmentation of the construction industry and the difficulties of coordinating the wide numbers of players and their tasks that slow down the introduction of innovative solutions, the construction sector has evolved in the last 25 years. This is especially driven by digital technologies and automation providing the construction industry with an opportunity to find innovative solutions to some of its rooted challenges. These innovations spanned across the whole project lifecycle, from design and engineering, through manufacturing and construction, to operation and maintenance, and retrofit/reuse/end-of-life. Among these, robotics is an emerging technological branch that can have an impact in construction areas such as off-site production, installation activities on-site, and operation and maintenance. This chapter will provide key insights about the digital transformation enabled by IER solutions in construction sites, analyze their current applications, limitations, and future developments, and propose an assessment framework to support construction actors in the decision-making process into the gradual adoption of IER for performing specific tasks.

8.3 ADVANTAGES AND BENEFITS OF IER

8.3.1 *Improving Safety*

The incident rate in the construction industry is the highest among various major industries in many countries (Choi et al., 2011). In the US, 25% of the fatal work injuries in 2020 belong to the construction sector (U.S. Bureau of Labor, 2021). In Great Britain, 1.8% of the construction workers reported a musculoskeletal disorder, which is the highest rate among the industries with similar work activities (Health and Safety Executive, 2021). Replacing humans by semi-autonomous and autonomous robots for undertaking unsafe tasks can reduce the number of incidents (Ilyas et al., 2021). Robots can be used for automating unsafe activities including heavy lifting and on-site inspection in dangerous work environments such as underground mines (Zimroz et al., 2019) and bridges (Lin et al., 2021). To reduce musculoskeletal injuries and physical fatigue of construction workers caused by repetitive and prolonged manual tasks, exoskeleton is being used for augmenting workers' physical ability (Brissi et al., 2022). Safety inspections and monitoring are other tasks that can be automated by robots for detecting unsafe locations (Martinez et al., 2020) and Personal Protective Equipment (PPE) on job sites (Ilyas et al., 2021).

8.3.2 *Improving Productivity*

Productivity growth has been a major concern in the construction industry as it was only one-third of the average total economy productivity growth over the past 20 years (Ribeirinho et al., 2020). Productivity of the construction industry can be improved by automating and robotising repetitive and labour-intensive activities. Autonomous transportation of construction materials by robots can improve productivity and eliminate human errors in these processes (Chea et al., 2020). For heavy lifting, robotic crane systems could improve productivity by 9.9–50% (Lee et al., 2009). The examples of IER applications for automation of different construction activity types are presented in Table 8.2.

8.3.3 *Addressing Skilled Worker Shortage*

Skilled worker shortage has been one of main issues in the construction industry over the past few years (Kim et al., 2020). The growing demand of construction workers and the aging workforces in many countries such as the UK (CITB, 2021; Green, 2021) are the main contributors to the

Table 8.2 IER application for improving productivity of different types of construction activities

Construction operation	*Robot application*
Masonry work	IER are used for automating bricklaying in masonry work. Hadrian X is the first mobile robotic bricklaying machine that uses 3D CAD model for accurately building masonry structures (FBR, 2022).
Precast concrete	IER are used for undertaking various tasks such as placing molds, reinforcement and distribution of concrete, and transportation of concrete formwork (Reichenbach & Kromoser, 2019; Saidi et al., 2016).
Steel component fabrication	IER are used for welding (Heimig et al., 2020), laser cutting (Bogue, 2008), bolting (Chu et al., 2013), and assembly (C. J. Liang et al., 2017) of steel components.
Timber construction	IER are used for cutting and drilling timber, and grasping, manipulating, and positioning building components (Eversmann et al., 2017; Willmann et al., 2016).

skilled worker shortage. In the long term, leveraging construction automation and replacing humans with IER can address this issue (Melenbrink et al., 2020). In addition, use of IER can address the challenges of the high labour wage in construction projects particularly in the metropolitan areas (Pan et al., 2020).

8.4 Key Use Cases for Intelligent Construction Equipment and Robotics

Although the impact of IER has not yet been fully realised in the construction industry (Carra et al., 2018), their applications are emerging to enhance construction productivity, safety management, quality control, and site planning issues. The first examples of construction robots were seen in the Japanese construction industry in the late 1970s and 1980s to supplement and replace workforce (Yilmaz & Metin, 2020). Construction automation and robotics application are classified in this chapter according to:

- Construction phase involvement—whether they are applied at the construction site (related to on-site activities) or at a factory for prefabrication activities (related to off-site activities) (Saidi et al., 2016). (Table 8.3);
- Level of autonomy—the second classification is based on the level of autonomy that IER technologies allow to perform (Table 8.4).

Table 8.3 Description of construction phase for IER classification

Off-site application	*Off-site* construction is widely used since the adoption of prefabrication approaches increase the control and the quality of the technological component manufactured. Indeed, the activities are conducted in a controlled environment as a factory with the consequence of reducing the risk of low quality during on-site installation. The adoption of IER solutions in a factory moves construction toward an industrialised sector with well-consolidated off-site activities.
On-site application	*On-site* execution is still a manual activity in many cases with the consequences of leading to problems such as unpredictable tasks and low levels of accuracy (Davila Delgado et al., 2019). The tasks during on-site stage are focused on the correct product installation, keep control of tasks advancement and monitoring with inspections activities the quality results. The traditional on-site activities require an appropriate level of labour skills to achieve the necessary efficiency in terms of construction duration and cost, and building quality (Yilmaz & Metin, 2020). On-site applications include: • **Construction**—phase which involves the installation of different materials and construction actions (bricks laying, concrete formwork, timber frame as described in Table 8.2). • **Inspection**—the objective of this task is to monitor the construction site activities in terms of time, quality, and cost. Technologies involved in this phase are equipped by a camera with the objectives to take pictures and share information regarding the construction site. Therefore, through the optimisation of the route, it reports in a regular range of time the work status verifying the correctness of installation. • **Maintenance**—this stage includes the set of actions to preserve the integrity and the functionalities of the building during its life. The different technologies installed in the building or infrastructure, mainly the active ones with a higher degree of deterioration and the ones subjected to external interference (e.g., weather conditions, users' utilisation) that require a scheduled plan of maintenance and control of performance over time (Fig. 8.1).

Table 8.4 Description of autonomy level for IER classification

Teleoperated systems	The system includes remote and human control systems. This fulfills industrial situations where there is danger to the operator and where remote-controlled machinery is necessary.
Programmable Construction Machines (PCM)	It includes most construction equipment that is outfitted with sensors and mechanisms to augment operation by an onboard human operator.
Intelligent systems	It relates to unmanned construction robots which operate in either a semi- or a fully autonomous mode. This category also referred to the concept of adaptive manipulation, imitation learning, improvisatory control, and full autonomy.

Fig. 8.1 Allianz Tower while human workers are cleaning the façade. (Credit: Piermario Ruggeri-Focchi façade)

IER technologies can be further classified based on their technology readiness level (TRL) which identifies the maturity of the technologies within the market. In particular:

- TRL < 5—implies technologies which have been prototyped;
- TRL 6–7—implies technologies which have been tested and validated in an operational environment;
- TRL > 8—implies technologies which are widely used on market, indeed are considered actual system/process completed, and qualified through test and demonstration (pre-commercial demonstration).

Table 8.5 shows TRL for different IER technologies. The TRL level has been assigned based on market and academic research.

Table 8.5 TRL of the available IER technologies (TRL <5 listed as "✓," TRL 6–7 listed as "✓✓," TRL > 8 listed as "✓✓✓")

Classification of construction automation and robotics								
Classification	*Off-site activities*	*TRL*	*On-site activities*					
			Construction	*TRL*	*Inspection*	*TRL*	*Maintenance*	*TRL*
Teleoperated systems	Exoskeleton	✓✓	Exoskeleton	✓✓	Drone	✓✓	Exoskeleton	✓
	–		Robotics arm	✓	Automatics monitoring	✓✓✓	Drone	✓
	–		Vehicles	✓	–		Automatics monitoring	✓✓✓
Programmable construction machines	Additive manufacturing	✓✓✓	Additive manufacturing	✓✓	Automatics monitoring	✓✓	Automatics monitoring	✓
	Robotics arm	✓	Robotics arm	✓	–		–	
	–		Integrated solution	✓	–		–	
Intelligent system	Robotics arm	✓✓	Robotics arm	✓	Automatics monitoring	✓	–	

The next subsections present some key examples of IER applications in the construction industry to highlight their significant impacts on various aspects of construction projects.

Additive manufacturing for construction phase—*MX3D Bridge* is a pedestrian bridge designed with generative design—complying between sustainable aspects and structural needs—and manufactured by exploiting the synergies between robotic and additive manufacturing. This is one of the first impactful examples for metal components moving from intelligent design to robotic-based production, validating the notion of the ability of such systems to move the construction sector into industrialised construction (MX3D Bridge, 2020) (Figs. 8.2 and 8.3).

Automatics monitoring for inspection—The potential of the combination between digital platform and inspection robotics is providing new opportunities for construction. This is well represented by the collaboration of Boston Dynamics and its sophisticated and movable robots SPOTWALK with HOLO BUILDER platform for the site project management controls which is revealing new digital workflows in the construction sector (HoloBuilder and Boston Dynamics Launch SpotWalk for Autonomous Reality Capture | Geo Week News | Lidar, 3D, and More Tools at the Intersection of Geospatial Technology and the Built World, 2020) (Figs. 8.4 and 8.5).

Unmanned Aerial Vehicle (UAV) for maintenance activities—UAVs could reach hazardous or high places, which is becoming a diffused

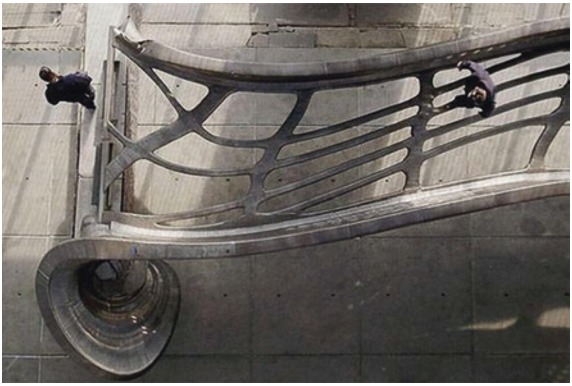

Fig. 8.2 MX3D Bridge. (Photo by Joris Laarman Lab)

Fig. 8.3 MX3D Bridge. (Photo by Adriaan de Groot)

Fig. 8.4 Spot robot for autonomous 360° photo capture. (Image courtesy of HoloBuilder)

practice with heightened expectations considering the opportunities that these technologies open to control the health of built assets. For instance, *Elios* is a UAV tool which inspects the photovoltaic (PV) panels with the aim of tracking and monitoring each cell to discover irregularities or loss of performances (Elios Aerial Thermography, 2021) (Figs. 8.6 and 8.7).

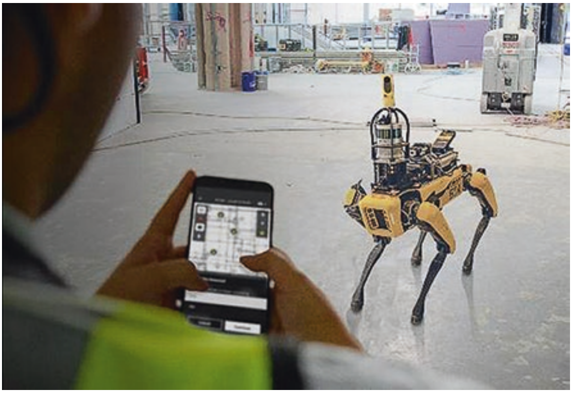

Fig. 8.5 HoloBuilder SpotWalk integration with Boston Dynamics. (Image courtesy of HoloBuilder)

Fig. 8.6 Thermography inspection of a PV plant by drone

Robotics arm in construction phase—*MULE* is a construction robot, flexible, portable, job-site ready lift assist which reduces time for lifting activities by 80% (MULE Lifting System | R.I. Lampus, 2021). ROB-Keller System AG have designed Robotic brickwork, *Rob*, to control the positioning of the masonry entirely positioned and controlled by the robotic arm. *Rob* allows to build walls even with shapes in compliance with

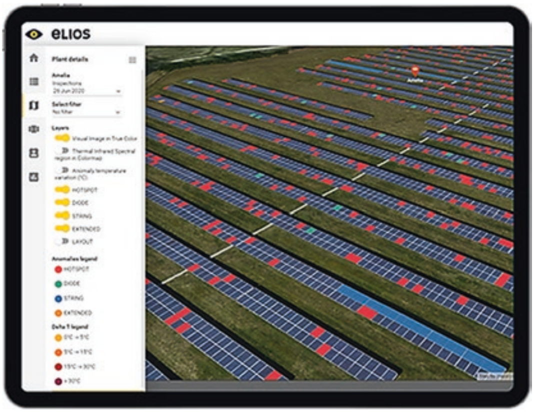

Fig. 8.7 Wesii digital platform: RGB view with colored anomaly classification

the calculations and resistance simulations made in the design phase (Robotic Brickwork, 2021).

Vehicles for construction phase—*HX2* is an autonomous and electric load carrier that can move heavy construction components. It has a vision system that allows the robot to detect humans and obstacles (Volvo CE Unveils the next Generation of Its Electric Load Carrier Concept, 2020).

Exoskeleton—*Eksovest* is an upper-body exoskeleton that supports arms during lifting activities (Exoskeletons Trialled on UK Construction Sites, 2021). *Exopush, developed by* Colas, is an exoskeleton designed to give power assistance to operatives working leveling with a rake. The exoskeleton improves the worker posture by reducing the stress movement of 30% (Colas Introduces the Exopush Exoskeleton to the UK, 2021). *G*-Ekso bionics has developed a robot which is able to hold heavy tools on aerial work platforms like scissor lifts and to standard scaffolding (EksoZeroG—Zero Gravity Tool Assistance, 2021).

Integrated solution—*Hephaestus*—A H2020 co-funded project has designed an IER tool for the installation of prefabricated building envelopes (Elia et al., 2018; Highly AutomatEd PHysical Achievements and PerformancES Using Cable RoboTs Unique Systems | HEPHAESTUS Project | Fact Sheet | H2020 | CORDIS | European Commission, 2020). The Hephaestus robot is composed of a cable-driven parallel robot (CDPR) and a modular End-Effector kit (MEE) which host tools and devices for the bracket positioning and façade modules installation. This robot expects in the next few years to provide a market autonomous solution for on-site tasks for installation of prefabricated envelopes, focusing on highly risky and critical construction tasks. The long-term purpose is to adopt Hephaestus not only for the installation stage but also for operations of maintenance and façade module replacement (Figs. 8.8 and 8.9).

Fig. 8.8 Cable-driven parallel robot installed in the demo building. (Credit Alex Iturralde)

Fig. 8.9 Hephaestus details during façade installation. (Credit Alex Iturralde)

8.5 IER for the Renovation Phase

In Europe more than 70% of the building stock was built before the 1970s and suffers from poor energy performance. Renovation is a key strategy to reduce the energy impact and the carbon footprint of buildings. The European Commission's target is to retrofit at least 3% of the building stock market by 2030. The retrofitting intervention involves changing in the building configuration to improve the energy performance while maintaining the occupant's comfort (Green Building 101, 2014). In this scenario construction automation and robotics can accelerate retrofitting interventions. For example, robotics applications support the existing workforce with on-site activities, which are currently based on crafts-oriented processes (Tellado, 2019). However, current key advantages of using robotics in retrofitting projects are focused on building data collection especially for the planning and design phase such as:

- Data collection regarding current building dimensions and shapes (survey). The utilisation of robotics as UAVs allows to collect accurate data in a reduced amount of time.
- Data collection regarding current building energy consumption by analyzing current building energy data, identifying areas with energy wastages, and understanding building energy use.

Robotics applications play a crucial role in addressing the challenges of building energy retrofit (Mantha et al., 2018). Accurate measurements, real time, and instant transfer of data can be integrated in the Building Information Modeling (BIM)[1] and exploited by relevant IER operations. A generic framework could be developed to support the data collected to arrive at an optimal building retrofit decision (e.g., most economical and most energy saving). Some examples are *Bertim* (*Refurbishment Solutions | STUNNING*), which is a H2020 project that aimed to enhance a building retrofitting intervention by integrating automation applications in the process, and *Vertliner* (*VERTLINER*)—an application-focused autonomous UAV that navigates inside the building, acquiring precise 3D data, images, or videos—to inform and update several layers of digital twin models and BIM representing the indoor environment.

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[1] Chapter 3 in this book present BIM in more detail.

8.6 CHALLENGES AND BARRIERS

Despite the advantages and benefits of IER, the construction industry has faced several challenges and barriers with their adoption as summarised in Table 8.6.

Table 8.6 Challenges for adopting IER in the construction industry

Challenge/ barriers	*Description*
High cost of capital	While use of IER can improve productivity and reduce the labour cost, it requires high capital cost, which is not affordable for the majority of construction companies that are small and medium size (Davila Delgado et al., 2019; Llale et al., 2019).
Unstructured and dynamic nature of construction sites	Unique and unstructured nature of the construction environment, dynamics of existing objects, and ambient conditions of construction sites (e.g., adverse weather conditions and existence of dust) have been major barriers for on-site applications of IER, limiting their mobility and communication (Ardiny et al., 2015; Carra et al., 2018).
Hazards of human-robot interactions	In the current state of the construction industry, fully automated construction is a long-term goal (Czarnowski et al., 2018) and integration of human and robot is imperative (Brosque et al., 2020). Interaction of human and robots in the construction industry is a major challenge because it is fraught with safety issues such as collision and distracting workers (McCabe et al., 2017). Ensuring a safe work environment for human-robot collaboration requires development of a formal safety standard (Liang et al., 2021) and a high cost for implementing safety measures (Davila Delgado et al., 2019).
Training and skills	Lack of continuous training and the required time and cost of training construction workers to operate and collaborate with IER are the main challenges of efficiently and safely using IER in the construction industry (Davila Delgado et al., 2019; Wang et al., 2021).
Cybersecurity[a]	Cybersecurity is a major concern for IER systems. Cybersecurity threats such as malicious misuse of the robots via cyber-attacks can cause serious financial losses and safety hazards to humans (Clark et al., 2017; Yaacoub et al., 2022).

[a] Chapter 9 in this book provides a more extensive discussion on cybersecurity and privacy considerations for deep renovation

8.7 Frameworks for Assessing and Implementing IER

A systematic approach to guide IER implementation is still missing in the construction sector (Hu et al., 2021; Pan et al., 2018). This section proposes a preliminary framework of indicators for assessing the advantages of using IER for buildings based on the current construction needs. The framework is designed for construction companies interested in evaluating whether robotic applications facilitate their planned tasks according to specific tasks' indicators. Using the selected metrics, the framework compares between the current manually handled tasks with the ones achievable by the adoption of a selected robotic technology. Hence, a quantitative ranking is used for the different tasks assigning a score for key macro indicators (quality, safety, time and cost) with the following scores:

- "-2" The robotic adoption hugely worsens task's indicators
- "-1" The robotic adoption worsens task's indicators
- "0" The robotic adoption does not affect task's indicators
- "+1" The robotic adoption improves task's indicators
- "+2" The robotic adoption hugely improves task's indicators

The total of all scores is a preliminary result to evaluate the IER for the selected activity: if the total score is positive, IER could facilitate the construction work, and if the total score is negative, IER will not improve the construction work.

The assessment framework is a preliminary decision support tool to facilitate the evaluation about advantages for IER adoption. More detailed investigation will need to be implemented to boost IER technologies adoption, especially once more solutions are available on the market. At this stage, the proposed framework can be considered an early-stage tool for navigating the advantages of emerging IER applications in the construction industry (Table 8.7).

Table 8.7 Framework of indicators for assessing the advantages of using IER for buildings

Frameworks for assessing and implementing construction automation and robotics

Building needs	Macro indicators and manual personnel managed						Use of robotics			
Tasks	**1. Quality**		**2. Safety**		**3. Time and cost**		**1**	**2**	**3**	**Tot**
	Pitfall	**Metric**	**Pitfall**	**Metric**	**Pitfall**	**Metric**				
Planning and designing phase	High number of actors in construction site	No of errors	Involvement of several actors in construction safety	No of hours for safety planning	High time-consuming	No of not valuable hours of work				
Designing in retrofitting intervention	Gap between existing building and survey	Level of accuracy	Existing building survey in dangerous place	Percentage of accidental/ fatal injuries	Gap between design and as-built	No of hours for rework				
Monitoring and inspection	Reliability of monitoring data	Accuracy of the data	Inspection in dangerous place	Percentage of accidental/ fatal injuries	High number of actors in construction site	No of errors and saving in labour cost				
Repetitive and heavy tasks	Loss of attention	No of errors	High number of long-term health injuries	Percentage of long-term health injuries	High number of long-term health injuries	Percentage of long-term health injuries				
High specialised activities	Shortage of skilled workers	No of errors	High time-consuming	No of hours for training	High wage for skilled workers	Saving in labour cost				
On-site activities in hazardous location	Low level of accuracy	No of hours for rework	Dangerous place activities	Percentage of accidental/ fatal injuries	Exposed activities	No of hours of human rope				
Workers' safety training	Low level of accuracy	No of hours for rework	High time-consuming	No of hours for training	High time-consuming	No of hours for training				
Building components manufacturing	Low level of accuracy	No of hours for rework	Loss of attention due to repetitive tasks	Percentage of accidental/ fatal injuries	High amount of waste materials	Percentage of waste cost				
							TOT			

8.8 Conclusion

There is emerging evidence that IER can benefit on-site and off-site construction operations. However, there are some challenges and barriers to overcome. From a contractor-side, economic factors including the high capital costs along with the costs pertaining to training and upskilling workers to operate IER are the main challenges. The nature of construction sites, which is generally unstructured, complex, and dynamic, entails further safety and operational challenges for using IER. Moreover, inadequate digitalisation levels within the construction industry limit the utilisation of IER. Tools for comparing traditional methods with advanced IER technologies are lacking in the construction industry. To contribute to these important gaps, this chapter classified the application of IER, reviewed key emerging applications and technologies, and proposed a framework to help assess the feasibility of implementing IER in construction. While some challenges to the adoption of IER are likely to persist in the short and mid-term, the emerging opportunities opened by IER have started to offer evidence about their disruptive nature and positive impact to quality, safety, and productivity in this key industry.

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