Journal of Building Engineering 26 (2019) 100868

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

Robotics and automated systems in construction: Understanding industry-specific challenges for adoption

Juan Manuel Davila Delgado, Lukumon Oyedele*, Anuoluwapo Ajayi, Lukman Akanbi, Olugbenga Akinade, Muhammad Bilal, Hakeem Owolabi

Big Data Enterprise and Artificial Intelligence Laboratory, Faculty of Business and Law, University of West of England (UWE) Bristol, Coldharbour Lane, BS16, 1QY, Bristol, UK

ARTICLE INFO

Keywords:
Automated construction
Robotics
Additive manufacturing
Exoskeletons
Autonomous vehicles
Off-site construction

ABSTRACT

The construction industry is a major economic sector, but it is plagued with inefficiencies and low productivity. Robotics and automated systems have the potential to address these shortcomings; however, the level of adoption in the construction industry is very low. This paper presents an investigation into the industry-specific factors that limit the adoption in the construction industry. A mixed research method was employed combining literature review, qualitative and quantitative data collection and analysis. Three focus groups with 28 experts and an online questionnaire were conducted. Principal component and correlation analyses were conducted to group the identified factors and find hidden correlations. The main identified challenges were grouped into four categories and ranked in order of importance: contractor-side economic factors, client-side economic factors, technical and work-culture factors, and weak business case factors. No strong correlation was found among factors. This study will help stakeholders to understand the main industry-specific factors limiting the adoption of robotics and automated systems in the construction industry. The presented findings will support stakeholders to devise mitigation strategies.

1. Introduction

The construction industry is one of the most important economic sectors across the world [13,44]. The spending in construction represents between the 9%–15% of GDP in most countries [72]; and up to half of nation's investment can be allocated to the built environment [72]. Despite its huge economic importance, the construction industry is beset with inefficiencies. Productivity in many sectors has been increasing steadily in the last five decades; however, productivity in the construction industry has barely increased, and it may have even decreased [50].

Robotics and automated systems have the potential to revolutionise and provide many advantages to the construction industry and to the Architecture, Engineering and Construction (AEC) area as a whole (e.g. Refs. [38,39,77]. Construction is a labour-intensive sector. Robotic systems and automation have proved to be very effective in other sectors for reducing labour costs while improving productivity and quality (e.g. Refs. [35,45,47]. Moreover, robotic systems can reduce injuries and free workers from conducting dangerous tasks [17]. [12] argues that conventional construction methods have reached their limits and that automation and robotics technologies have the potential to address the productivity challenges of the construction industry.

Robotics systems for construction were developed since the 1960s and 1970s at the same time when other industries started their automation, e.g. the automotive industry [12]; however, the adoption of robotics in the construction industry has been very slow [54]. note that the degree of automation in construction lags other industries. A research study [70] with 11 large construction companies and government agencies in Europe reports that while companies perceive that robotics and automated systems will improve productivity and health and safety, there are significant risks to adoption including high costs for implementation and high commercial and technical risks [13]. also notes that the construction industry has been slow to adopt not only robotics but new technologies in general; but [13], argues that automation and robotics are affecting the sector as a whole significantly and that they will play an active role on the future developments of the industry. Other technological developments like the Industry 4.0 paradigm, Building Information Modelling (BIM), sensing technologies,

---

* Corresponding author.

E-mail addresses: manuel.daviladelgado@uwe.ac.uk (J.M. Davila Delgado), l.oyedele@uwe.ac.uk (L. Oyedele), anuoluwapo.ajayi@uwe.ac.uk (A. Ajayi), lukman.akanbi@uwe.ac.u (L. Akanbi), olugbenga.akinade@uwe.ac.uk (O. Akinade), muhammad.bilal@uwe.ac.uk (M. Bilal), hakeem.owolabi@uwe.ac.uk (H. Owolabi).

https://doi.org/10.1016/j.jobe.2019.100868
Received 20 January 2019; Received in revised form 9 July 2019; Accepted 9 July 2019

and artificial intelligence (e.g. Refs. [24–26] have the potential to drive the adoption of robotics in the construction industry as well [72,86].

While robotic and automated systems for construction have been developed since the 1960s, and there are many applications for their use in the construction industry [57]. There are still many factors that limit the adoption of robotics in the construction industry, and there have been insufficient research efforts to address them. For example [64], presented a detailed study on the barriers affecting the adoption of Robotics in Japan, Malaysia and Australia. However, very few other research has been reported in literature [92]. have identified the significant challenges facing the future development of the robotics field in general. The authors note that while there is a big potential for robotics in the construction industry, domain-specific challenges have not been thoroughly investigated. The low levels of adoption indicate that there is a clear need for up-to-date studies and additional discussions on the factors that limit adoption. This study seeks to cover this gap with a systematic investigation of industry-specific challenges for adopting robotics in the construction industry. The objectives of this study are:

(1) To identify, categorise, and rank the most important challenges that are limiting the adoption of robotics in the construction industry.
(2) To understand the expectations of stakeholders regarding the adoption of robotics in the construction industry.

In order to achieve these objectives, a literature review of challenges and limitations was carried out; then, a qualitative study was conducted using focus group discussions to understand the stakeholders view on the subject. Lastly, a quantitative analysis was performed to rank the identified factors limiting the adoption of robotics in the construction industry.

2. Robotics and automated systems in construction

This section presents a brief overview of the different types of robotic and automated systems used in the construction industry. These systems are varied, and there is no consensus regarding a defined categorisation. The lines between categories are constantly moved or blurred by new developments in technologies. The categorisation presented here intends to facilitate the understanding of a very complex and varied technology landscape and to provide the reader with a quick overview of the different types of systems. The categorisation presented here is partly based on the work by Ref. [12].

The types of automation and robotic technologies for construction can be grouped in four general categories (see Table 1): (1) Off-site prefabrication systems, (2) On-site automated and robotic systems, (3) Drones and autonomous vehicles, and (4) Exoskeletons. The first construction robots were developed in Japan to increase the quality of building components for modular homes [11]. (Category 1: Off-site prefabrication systems). The adoption of these robots was the result of the successful use of robots in the automotive manufacturing sector in Japan. Later, construction robots started appearing on construction sites, and automated construction sites systems were developed (Category 2: On-site automated and robotic systems) [11]. The latest developments have been robots and autonomous vehicles for inspection, monitoring, maintenance, etc. (Category 3: Drones and autonomous vehicles). Lastly, exoskeletons are wearable mechanical devices that augment the capabilities of the user. Note, that exoskeletons are not strictly a robotic system, because they augment the capabilities of the worker instead of replacing it altogether. However, it was decided to include exoskeletons here because this study focuses on all hardware technologies that improve construction activities. Also, in the future, this distinction will not be as clear cut. For example, exoskeletons require a high degree of automation and a considerable potential exists on human-robot collaboration [1,92]. In this sense, before construction sites are entirely devoid of human workers, it can be expected that robots, automated systems and augmented workers will work together seamlessly.

2.1. Off-site automated prefabrication systems

This category includes various technologies that produce building components at off-site locations in an automated manner. The main objective of these systems was to improve the quality of prefabricated building components and took inspiration from the use of robots in other manufacturing sectors. According to Ref. [12]; these technologies include building component manufacturing (BCM) approaches, which transform materials (concrete, bricks, wood, steel, etc.) and low-level components into high-level building components. For example, concrete prefab elements, steel trusses, wood structural elements, wall, floor and roof sections, etc. There are also large-scale prefabrication (LSP) approaches, which combine high-level building components into finished entire building modules (e.g. bath or kitchen modules). This category also includes additive manufacturing techniques, also known as 3D printing. There is a large number of publications reported in literature regarding the use of additive manufacturing techniques in the construction industry. The prospects, challenges and benefits of 3D-printing technologies for the construction industry have been widely reported in literature [76,85]. The main challenges identified include the development of appropriate materials and the lack of understanding of the material mechanical performance [91]. Various potential applications have been identified, ranging from the creation of optimised and customised building parts to in-situ repairs [28]. Additive manufacturing technologies have been improving rapidly, and now, it is possible to print large scale components as well [61,94].

2.2. On-site automated and robotic systems

This category includes automated and robotic systems that can be used directly on the construction site to create structures and buildings. The first type of systems used were single task construction robots (STCRs), which can execute a single task in a repetitive manner. A typical example of this type of robots is robotic arms used in automotive manufacturing. These types of robotic arms are usually mounted in movable platforms and are used on site to perform simple tasks. For example [31], presented a scaffold integrated robotic system that enables a robotic arm to be mounted in a scaffold [49], presented a robotic system that paint walls [30], presented a mobile robotic arm that assembles bricks, and [89] presented a concrete spraying robotic system. This approach is very flexible because it could be easily adapted to be used in combination with other traditional construction methods. However, this approach generates other challenges such as the need for additional health & safety requirements, the difficulty to parallelise and to integrate with human workers activities, and the lack of integration with downstream and upstream activities. Robotic on-site factories have been developed to address these challenges. They are factory-like environments on construction sites. Its main intention is to integrate standalone STCRs into controlled environments that enable the implementation of networked robot systems, in which various robots can be used for different types of task in an automated manner, resembling a manufacturing production line. In this same note, research has been carried out that seeks to enable collaboration among various robots to complete more complex tasks. For example [40], presented a feasibility study to use various robots to build masonry structures [53]. presented a hardware-software system that enables small robots to assemble and disassemble plastic blocks.

2.3. Drones and autonomous vehicles

This category includes terrestrial, aerial or nautical vehicles that can be piloted remotely, or which are autonomous (i.e. no conductor is required). These vehicles can be used for various tasks including (1) accessing extreme and dangerous environments, thus removing human workers from high-risk areas; (2) surveying and monitoring tasks; and (3) automated excavating, demolition and transportation of materials.

Table 1
Examples of robotic, automated and autonomous systems in the construction industry.

Category	Description, types and use-cases	References
1. Off-site automated prefabrication systems	Production of building components at off-site locations in an automated manner	
	● Building component manufacturing (BCM)	[7]
	● Large-scale prefabrication (LSP)	[48] [61] [62]
	● Additive manufacturing (3D printing)	[76] [85] [91] [94]
2. On-site automated and robotic systems	Automated and robotic systems used directly on the construction site	
	● Single task construction robots (STCRs) for bricklaying, steel-truss assembly, steel welding, façade installation, wall painting, concrete laying, etc.	[9] [83] [49] [31] [30] [89]
	● Robotic on-site factories	[8] [58] [5]
	● Swarms and robots for building component assembly	[53] [40] [69]
3. Drones and autonomous vehicles	Terrestrial, aerial or nautical vehicles that can be piloted remotely or which are autonomous.	
	● Access to extreme and dangerous environments	[90] [29] [82] [67]
	● Surveying, inspection and monitoring	[75] [6]
	● Automated drilling, excavation and earth moving	[15] [21,22] [56]
4. Exoskeletons	Wearable devices that work together with the user as opposed to a robot which performs the task autonomously.	
	● Improve workers productivity: lift heavy loads, reduce fatigue, and facilitate the use of tools in awkward positions.	[10] [27]
	● Reduce injuries	[4]

Drones can be used to sample extreme environments and to study harsh and unreachable sites [90]. For example, drones have been developed to access and monitor mud eruption zones [29] or even space exploration [82]. The main use-cases for aerial drones are surveying and monitoring tasks [78]; but terrestrial drones have been developed for these tasks as well. For example, a terrestrial drone has been reported in literature to automate visual bridge inspections [75], as well as a vehicle that navigates construction sites and collects data for progress monitoring [6]. However, the main application of terrestrial vehicles has been the use of autonomous vehicles and excavators for mining [15]. Drillers and excavators have been automated, and GPS-enabled driverless trucks transport the excavated material in-between locations. The relative simplicity of mining operations tasks, as compared with traditional construction tasks, have enabled the adoption of these technologies. However, for traditional construction sites, there are still many challenges in the automation of earth-moving machines [21]. Also, there are many challenges to be addressed so that drones can be used effectively for construction [59,74], including: (i) high initial costs; (ii) low battery life, which restricts operations; for example, most drones have a flight time of fewer than 30 min; (iii) complex operability of hardware and software, which requires additional training and increases costs; (iv) false perceived levels of accuracy and tolerances, which could lead to errors and accidents; (v) stringent regulations that increase adoption costs; and lastly (vi) that drones represent additional risks to health and safety.

2.4. Exoskeletons

Exoskeletons are wearable devices that work together with the user as opposed to a robot which performs the task autonomously instead of the worker. Exoskeletons are mechanical devices, worn by the worker, which amplify human performance. Exoskeletons can help construction workers to reduce the high-impact of their job and to improve their productivity by allowing them to lift heavy loads, reduce fatigue, facilitate the use of tools in awkward positions, etc. [10,27]. Exoskeletons can also contribute to reduce injuries and to maintain a healthier workforce [4]. This is of extreme importance as the repetitive and physically demanding tasks carried out by construction workers can lead to severe strain, injuries and permanent disabilities [79]. In addition, exoskeletons can be a solution to the challenges presented by an ageing construction workforce [66], by enabling older workers to continue working on site and carrying out physically demanding tasks. However, there are still many challenges to be addressed, including high costs, energy efficiency, safety, and comfortability [18,41]. Regarding the construction industry specifically [55], reported the perceived barriers for using exoskeletons including (i) Safety and health concerns as using exoskeletons could increase catch, snag and fall risks; hygiene issues; and a false sense of safety. (ii) Usability concerns, including durability, ruggedness, and versatility. Construction equipment usually is subjected to hard conditions due to the nature of construction activities conducted outdoors in all-weather conditions. Exoskeletons must be capable of enduring these harsh conditions while remaining comfortable and safe to use. (iii) The lack of integration with other

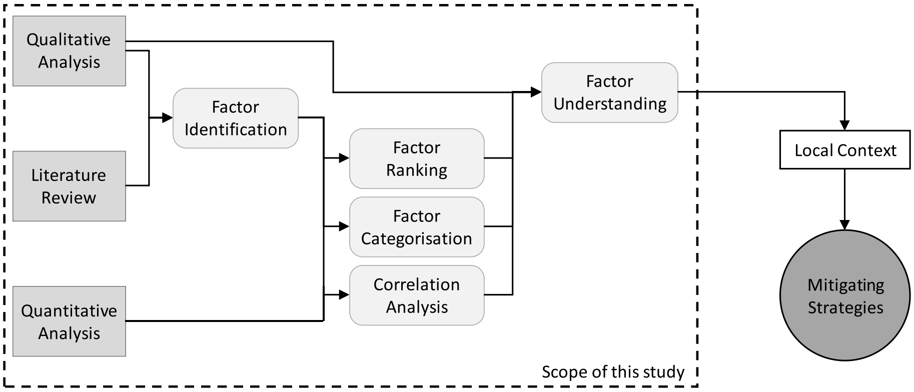


Fig. 1. Diagram showing the research methodology used.

personal protective equipment (PPE). (iv) The initial high costs of adoption and the need for a quick return on investment. Lastly, (v) a significant barrier is the possible low acceptance rates by workers.

3. Research methodology

A mixed research method was used that combines (i) literature review, (ii) qualitative data collection and analysis, and (iii) quantitative data collection and analysis [19]. This type of mixed research methods has been proved as powerful tools to investigate complex processes and systems in other sectors [36]. This type of mixed methods can also be very beneficial in the AEC area, in which qualitative results can support and guide the quantitative data collection and analysis. Combining qualitative and quantitative analyses helps to explain, categorise and generalise findings [36]. Fig. 1 presents a diagram of the research methodology used and the scope of this study. The first step was to conduct a review of the existing literature on factors that limit the adoption of robotics in the construction industry. In addition to this, focus group discussions (FGs) (qualitative analysis) were used to identify limiting factors that may not have been identified in the literature. Findings from both activities were compiled into a single list of factors. In the second step, quantitative analysis, the results from the previous step were used to design a quantitative data collection instrument (i.e., questionnaire). The questionnaire was administered to specialists in the AEC area in European countries. The identified factors were ranked and categorised (using component analysis), and correlations among them were investigated using the results of the questionnaire. A reliability analysis was carried out on the questionnaire results to validate the internal consistency of the results. Lastly, using the results of the qualitative and the quantitative analysis relevant insights into the factors limiting the adoption of robotics in the construction industry were drawn and explained (factor understanding). The results of this study can then be analysed based in a local context (e.g. a specific country, company and project) and mitigating strategies can be devised to address the specific challenges that limit the adoption of robotics in the construction industry.

4. Qualitative sampling and analysis

Three FGs were used to collect the opinion of experts on the field regarding factors limiting the adoption of robotics in the construction industry. FGs are very well suited for exploratory analysis as allow the participants to build on arguments from the other participants, which is not the case with individual interviews. Twenty-eight experts from industry and academia participated in 3 cross-disciplinary discussions with a duration of 45 min each. The years of experience of the participants ranged from 6 to 20 years. An overview of the participants and the FGs are presented in Table 2.

Table 2
Overview of the focus groups.

FG	Category	No of experts
1	◆2 University researchers ◆2 Contractors ◆1 Architect/Designer ◆2 Engineering consultants ◆2 Technology developers ◆2 BIM managers	11
2	◆2 University researchers ◆2 Contractors ◆2 Engineering consultants ◆1 Technology developer ◆2 BIM managers	9
3	◆2 University researchers ◆1 Contractor ◆1 Architect/Designer ◆2 Engineering consultants ◆1 BIM manager ◆1 Standard developer	8

A type of thematic analysis (e.g. Ref. [14] was used for the qualitative part of the study, which includes: (1) data familiarisation, (2) data coding and segmentation, (3) development of themes and (4) grouping of related themes. Table 3 presents the combined findings from the literature review and the FG analysis. Factors identified in literature and in FGs were grouped in the following themes: workforce challenges, economic challenges, cultural challenges, industry-intrinsic challenges, and research & development (R&D) challenges.

5. Quantitative sampling and analysis

Eleven factors that limit the adoption of robotics in the construction industry were defined based on the findings of the literature review and the qualitative analysis (see Table 4). The final list of factors included the most mentioned and discussed factors during the FGs; and new factors extracted from recent literature (from 2016 onwards) that were not discussed during FGs. Then similar factors were combined and rephrased to improve clarity.

A questionnaire was designed to validate and quantify the importance of the eleven factors. A 1 to 5 Likert scale was used in the questionnaire to codify the responses, in which 1 corresponds to the lowest importance and 5 to the highest importance. The questionnaire was pilot-tested by 4 experts (2 from industry and 2 from academia) to ensure the clarity of the questions and the structure of the questionnaire. Experts from construction companies, engineering consultancies, design firms and academia were approached to complete the questionnaire. The participants were selected as follows: 10 from the top construction companies by revenue, 10 from small and medium construction companies, 10 from the top engineering consultancy companies by number of employees, 10 from small and medium

Table 3
Preliminary mapping of the factors that limit the adoption of robotics in construction.

Factors and Themes	References in Literature	Focus Groups		
		1	2	3
Workforce Challenges				
Lack of continuous training		✓		
Unskilled workforce	[17,44]	✓	✓	✓
Ageing workforce	[12]			
Economic Challenges				
High initial capital investment		✓	✓	✓
Capital intensive	[12]	✓	✓	✓
Low return on investment			✓	
Business models and contracts stifle collaboration	[51]	✓	✓	✓
Cultural Challenges				
Aversion to change		✓	✓	✓
Very established industry	[12,17]	✓	✓	✓
Job security		✓	✓	✓
Robot-human interaction	[92,93]			
Industry-intrinsic Challenges				
Fragmented industry	[51,86];	✓		✓
Project-based industry	[17,43]		✓	
Intense competition	[43]			
High-risk industry	[17]	✓	✓	
Low profits	[17]	✓	✓	✓
Predominance of SME's in the sector	[44]		✓	
Conflicting interests in supply chain	[51,77]		✓	✓
Subpar collaboration in supply chain	[68,77]	✓		
Poor information exchange	[51,86]	✓	✓	✓
Significant duplication of efforts	[51]			
Product complexity	[12,53];	✓	✓	
Limited use of digital modelling	[43]			✓
R&D Challenges				
Low R&D investment	[12,37,43]			✓
Narrow scope of R&D	[37]			
Weak innovation culture	[65]	✓	✓	✓
Complex implementation	[12]		✓	

Table 4
Reliability analysis and ranking of factors.

Label	Factors	Rank	Mean	Cron. Alpha*
L2	High initial capital investment	1	4.33	0.744
L10	No strong need to improve productivity	2	4.11	0.737
L7	Low R&D budgets in the construction industry	3	3.86	0.733
L5	Current work culture/aversion to change	4	3.83	0.747
L1	Untrained workforce	5	3.81	0.759
L3	Unproved effectiveness/immature technology	6	3.56	0.759
L9	Easy access to labour	7	3.53	0.725
L4	Low return on investment/insufficient demand	8	3.39	**0.770****
L11	Lack of government incentives	9	3.39	0.726
L8	Decreasing public infrastructure budgets	10	3.28	0.743
L6	Fragmented nature of the construction industry	11	3.19	0.708

Overall Cronbach's Alpha = 0.76.
Overall Gutman's lambda-2 = 0.779.

engineering consultancy companies, 10 from top design firms by number of employees, 10 from small and medium design firms, and 10 from academia. In total, 70 experts were contacted, and 36 completed questionnaires were received, which represents a 51.4% response rate. The distribution of the respondents is as follows: 16.7% have up to 5 years of professional experience, 38.9% up to 10 years, 25% up to 20 years, and 19.4% more than 20 years. Around 80% of the respondents indicated that they have very high or high expertise with new digital technologies in the construction industry.

Fig. 2 presents a Letter-Value plot of the distribution and ranking of the importance of the investigated factors. It is a modified box plot that presents more quantiles and tail behaviour, which gives a quick, clear indication of the response distribution for the 11 investigated factors. The most important factor, according to the quantitative analysis, is (L2) "*High initial capital investment",* followed by (L10) "*No strong need to improve productivity*". The least important factors are (L6) "*Fragmented nature of the construction industry*", followed by factor (L8) "*Decreasing public infrastructure budgets*". Fig. 2 also shows the mean and median of the responses of all factors. With the exception of L2 and L10, all the factors have similar means and medians. This indicates that all the respondents assigned similar importance to all the factors.

The correlation among factors was also investigated (see Fig. 3). None of the factors has a strong correlation with each other. The factors that present weak correlations are (i.e. correlation factor >0.6 & <0.7): "*Decreasing public infrastructure budgets*" and "*Easy access to labour*" (L8 and L9 = 0.65), "*Low R&D budgets in the construction industry*" and "*Fragmented nature of the construction industry*" (L7 and L6 = 0.61). The correlation of factors L6 and L7 is also indicated in the component analysis presented below.

5.1. Reliability analysis

A reliability analysis was conducted to test the internal consistency of the factors included in the questionnaire. The overall *Cronbach's Alpha* for this study is 0.76, which is a correlation estimate for randomly equivalent measures; while the overall *Gutman's lambda-2* is 0.779*,* which estimates correlation for parallel measures. Both measures indicate acceptable internal consistency of the data collected in the questionnaire [71]. Table 4 presents the ranked factors according to their mean. The highest ranked factor is (L2) *High initial capital investment*; while the lowest ranked factor is (L6) *Fragmented nature of the construction industry*. Table 4 presents the "Cronbach's Alpha if deleted", which identifies factors that may not contribute to the reliability of the dataset and thus can be omitted. The only factor that falls, in this case, is factor L4, Cronbach's Alpha if deleted = 0.77, which is slightly higher than the overall Cronbach's Alpha (0.76). However, this difference is not significant, and factor L4 was kept in the analysis.

5.2. Component analysis

Principal Component Analysis (PCA) was carried out to investigate the underlying dimensions of the studied factors and to identify a smaller set of correlated principal factors. PCA is an unsupervised learning technique used to simplify the complexity of high-dimensional data, while retaining relevant patterns. In this case, PCA was used to generate 4 components that group similar and related factors. These four components account for ~70% of the variance, as presented in Table 5. The components, which are abstract groupings, were interpreted into categories and named based on the assigned factors. Category (C1) accounts for 31.31% of the variance (% σ^2), category (C2) for 15.05%, and C3 and C4 account for 12.21% and 10.74% (Table 5). In total, these four categories capture and explain ~70% of the underlying characteristics of all the analysed factors.

The defining factor loading (*f*) for each factor and the standard deviation of loading factors per factor are also presented in Table 5. Factor loadings provide an indication of how well the generated components represent the underlying factors. Note that, factor loadings higher than 0.5 are considered as acceptable. In this case, only factor (L3) has a slightly lower factor loading than 0.5, i.e. 0.492; however, it was decided to assign it to component C3 because the difference is negligible. Overall, the analysed data is suitable for PCA, as the Kaiser-Meyer-Olkin Measure of Sampling Adequacy is higher than the acceptable level (i.e. 0.50), and the significance level of Bartlett's Test of Sphericity is lower than 0.05 [42] as shown in Table 5. The approximate Chi-Square is 123.285 with 55 Degrees of Freedom.

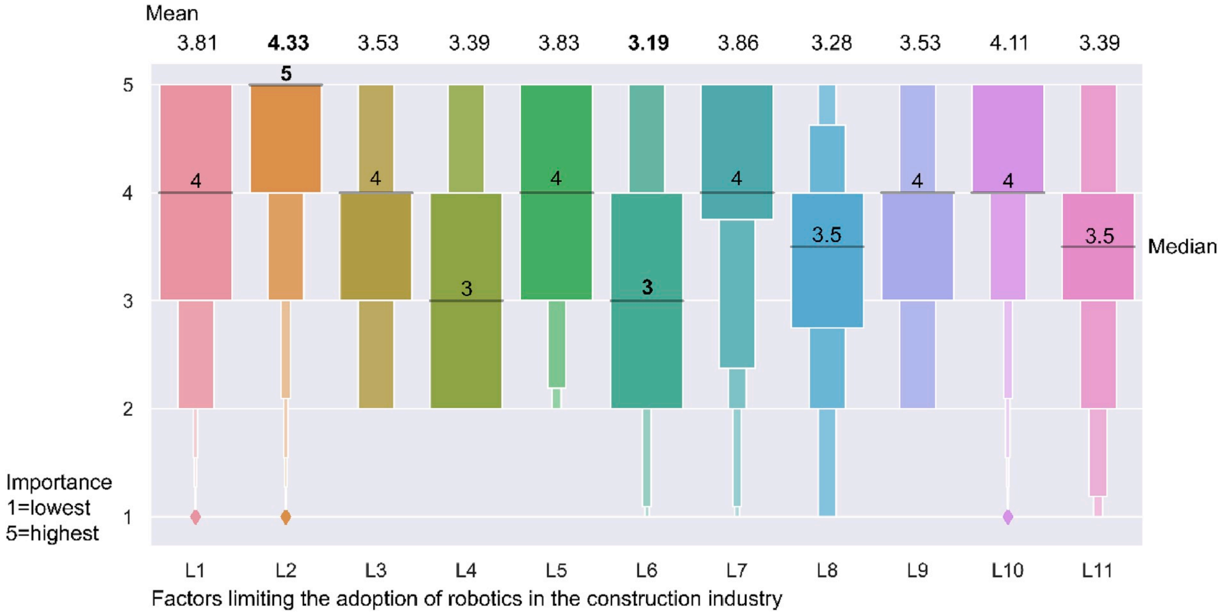
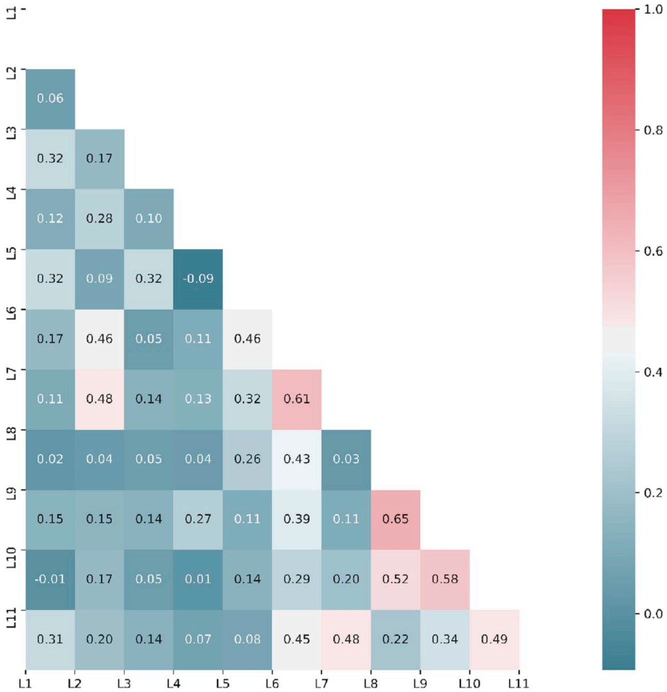


Fig. 2. Overview of the importance of the factors that limit the adoption of robotics in the construction industry. Factor **L1** (High initial capital investment) is the highest ranked factor, and factor **L6** (Fragmented nature of the construction industry) is the lowest ranked factor.



	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11
L1											
L2	0.06										
L3	0.32	0.17									
L4	0.12	0.28	0.10								
L5	0.32	0.09	0.32	-0.09							
L6	0.17	0.46	0.05	0.11	0.46						
L7	0.11	0.48	0.14	0.13	0.32	0.61					
L8	0.02	0.04	0.05	0.04	0.26	0.43	0.03				
L9	0.15	0.15	0.14	0.27	0.11	0.39	0.11	0.65			
L10	-0.01	0.17	0.05	0.01	0.14	0.29	0.20	0.52	0.58		
L11	0.31	0.20	0.14	0.07	0.08	0.45	0.48	0.22	0.34	0.49	

Fig. 3. Diagram showing the correlation among factors. The factors that present weak correlation are: L8 and L9 = 0.65, L7 and L6 = 0.61.

Category 1 (C1), it was titled "*Contractor-side economic factors*" and includes six factors out of the eleven tested: (L2) High initial capital investment, (L6) Fragmented nature of the construction industry, (L7) Low R&D budgets in the construction industry, (L9) Easy access to labour, (L10) No strong need to improve productivity, and (L11) Lack of government incentives. This category includes the highest number of factors of all the four categories and accounts for the highest % of variance (Table 5). Category 2 (C2), it was titled "*Client-side economic factors*" and includes only one factor: (L8) Decreasing public infrastructure budgets. Category 3 (C3), it was titled "*Technical and work-culture factors*" and includes three factors: (L1) Untrained workforce, (L2) Unproved effectiveness/immature technology, and (L3) Current work culture/aversion to change. Lastly, category 4 (C4) was titled "*Weak business case*" and includes only one factor: (L4) Low return on investment/insufficient demand. These four categories represent the main factors limiting the adoption of robotics in the construction industry, which are discussed in the next section.

6. Types of factors limiting the adoption of robotics in the construction industry

6.1. *Contractor-side economic factors*

This category encompasses all the factors that relate to the costs that construction companies must incur to adopt robotics in construction; it does not include economic factors affecting the clients or infrastructure owners. This category includes the two highest ranked factors: (L2) "High initial capital investment" and (L10) "No strong need to improve productivity". Regarding factor L2, the high cost of adopting solutions that replace manual labour are well known from other sectors, and its influence on adoption is evident. The high initial capital investments are justified because they will reduce expensive manual labour and increase productivity. However, for many construction companies, these advantages are not always realisable. In a sector where the majority of the companies are small subcontractors and where only a few big construction companies can assign resources to test new technologies, high capital investments represent a major challenge.

Regarding factor L10, low-productivity has been identified as a central characteristic of the construction industry for many years (e.g. Refs. [3,80]. According to this study, there is not a strong motivation from contractors to improve in this regard. Note that from the client's or infrastructure owner's point of view, this might be different. This finding can be explained, and it is reinforced by some of the other factors grouped in this category, e.g.: (L9) "*Easy access to labour*". In other sectors (e.g. automotive), it has been identified that easy access to labour reduces the pace at which automation is adopted. It is a similar situation for the construction industry, in which access to labour has not been a significant problem in recent decades; and therefore, it limits the adoption of robotics. Secondly, (L11) "*Lack of government incentives*", is also perceived as a limiting factor for improving productivity.

This category also includes the lowest ranked factor: (L6) "Fragmented nature of the construction industry". The results of this

Table 5
Four components were extracted. Extraction method: Principal Component Analysis. Each cell presents the standard deviation of each component.

Label	Categories and factors	% of variance (% σ^2)	Factor loading (f)	STDEV of every f $s(F)$
C1	*Contractor-side economic factors*	31.31%		
L2	High initial capital investment		0.502	0.383
L6	Fragmented nature of the construction		0.795	0.417
L7	Low R&D budgets in the construction industry		0.628	0.430
L9	Easy access to labour		0.677	0.431
L10	No strong need to improve productivity		0.637	0.410
L11	Lack of government incentives		0.673	0.308
C2	*Client-side economic factors*	15.05%		
L8	Decreasing public infrastructure budgets		0.603	0.431
C3	*Technical and work-culture factors*	12.21%		
L1	Untrained workforce		0.529	0.083
L3	Unproved effectiveness/immature technology		0.492	0.068
L5	Current work culture/aversion to change		0.539	0.341
C4	*Weak business case*	10.74%		
L4	Low return on investment/insufficient demand		0.756	0.395
Cumulative % of variance		**69.31%**		

Kaiser-Meyer-Olkin Measure of Sampling Adequacy: 0.597.
Bartlett's Test of Sphericity; Approx. Chi-Square: 123.285, Degrees of Freedom: 55, Significance Level: 0.000.

study indicate that the complex and varied supply-chain required to deliver construction projects and the poor knowledge exchange [2] do not play a major role for the adoption of robotics. The other factor in this category is (L7) "Low R&D budgets in the construction industry", which is characteristic of the construction industry and has been documented in literature when compared with other sectors such as the manufacturing and automotive sectors [44].

In summary, contractor-side economic factors represent the most notable limitation to the adoption of robotics in the construction industry. This is expected as construction is a low-profit and high-risk industry, in which the adoption of new technologies is not feasible in practice and can affect the survivability of the companies. For example, the average profit margin of the top 100 UK construction companies was just 1.5% in 2017 (TCI, 2018). In other sectors where the profit margins are much higher such as the automotive or manufacturing sector, there is more opportunity to test new technologies.

6.2. Client-side economic factors

The main factor in this category is the cost that the client must incur for adopting robotics. It includes factor (L8) Decreasing public infrastructure budgets. This factor identifies the low infrastructure spending across most of the industrialised world in the last decades as a limitation for adoption. For example, the [34] identified the infrastructure spending in 2017 as the lowest in 20 years. Governments are the major clients of all construction and infrastructure companies, and the amount of public spending in infrastructure has a big influence on the adoption of new technologies. In addition, the current tendering practice that prioritises "lowest price" as the most important criterion to award projects represents a big limitation to innovation [87]. In a highly competitive market, if the price is the only selection criteria, construction companies tend to reduce profit margins aggressively, and the adoption of new technologies is restricted. Furthermore, this practice can lead to confrontational behaviour and restricts alternative thinking [63]. Other alternative selection methods exist, e.g. Most Economically Advantageous Tender (MEAT), which includes other criterion besides price such as quality, sustainability, technical and innovative merits, etc. It usually consists of two evaluation phases: an initial technical evaluation phase and a secondary financial evaluation phase. There are various manners to implement MEAT approaches depending on the weighting and formulas used to select the best bid [84]. However, limited infrastructure budgets and short-term decision-making prevent the adoption of new evaluation approaches (e.g. Ref. [46]; reinforcing a negative and mutually-feeding cycle of low-price and low-innovation.

6.3. Technical and work-culture factors

This category includes the practical factors that limit the implementation of robotics. These factors concern the technical limitations of current technologies and work-culture related factors. Factor (L3) Unproved effectiveness/immature technology, highlights the concerns from industry stakeholders regarding the readiness of robotics to be used in construction. These views have been identified in other studies as well. For example, in a set of interviews with 11 of the top construction companies and infrastructure providers in the UK, it was found that technical issues of adopting robotics is the second most important barrier to adoption [70]. The first barrier identified is the high complexity of construction tasks that limits the usability and effectiveness of robotic and automated solutions.

Human-robot interaction is also a significant challenge for robotics adoption in general, as described by Ref. [92]. But for the construction industry, it is a critical factor given its labour intensive tasks and the expected gradual adoption of robotics. Effective collaboration between humans and robots will be essential for successful adoption. However, there is very little research that can explain and address the complexity of this interaction. For example [93], highlighted the lack of studies and theoretical models to predict and explain the perceived safety of construction workers working alongside robots. The authors noted that the high implementations costs for testing human-robot interaction are prohibitively-expensive; and therefore, they developed a testing environment using a virtual reality system. The authors found that there is a common aversion of workers to performing tasks alongside robots and that strictly defined physical areas for robot and human task can be beneficial. Another area with knowledge gaps is the operational requirements for human-robot interfaces [20]. note that the development of robots for construction should consider the specific operational needs of the machine-robot interaction for construction tasks. This is an important consideration as many of the robots used in construction have been adapted from robots designed for other manufacturing activities in other industries (e.g. automotive, etc.).

This category also includes factor (L1) "Untrained workforce"; which can be very relevant as skill gaps in construction workers have been identified as potential barriers to meet low-energy construction targets [81]. In this regard, the structure of the construction labour markets can also be a barrier for upskilling and that employers should engage actively to support skills development [88]. Another factor grouped in this category is (L5) Current work culture/aversion to change, which highlights the effects of the weak innovation culture prevalent in the construction industry [65].

6.4. Weak business case

The main factor in this category is the unclear value that construction companies can obtain from adopting robotics. It includes factor (L8) Low return on investment/insufficient demand. The central underlying aspect of this category is that there is no hard evidence that adopting robotics will genuinely represent a cost reduction in the delivery of assets. The construction industry is a low-profit and high-risk sector; in which this lack of evidence represents a massive obstacle. More specifically, there are no complete and thorough cost/benefit studies for adopting robotics reported in literature, as they are studies regarding sustainability, for example [73]. It is widely acknowledged that the adoption of robotics has the potential of reducing costs related to labour and injuries. In that same sense, robotics systems are considered as an expensive technology. However, the cost includes the robotic systems, but also software, skilled engineers, and training. Moreover, ensuring safe working environments that include robots is very expensive [60]. Potential time savings have been investigated, for example [77], have estimated that using robots for specific construction tasks can save up to 50% of the time required. However, these types of studies focus on particular tasks and do not consider the time and cost implications of additional training and safety requirements.

The other challenge included in this category relates to the insufficient demand for robotics and automated systems. One of the limitations of these systems is the lack of flexibility and customisation. In the construction industry, in which every project is different and almost every client is different as well, there is less certainty that the investments made to implement robotic systems can be exploited in future projects with different clients. For example, regarding prefabricated building components [33], found that there is no sufficient demand for prefabricated construction components, they represent a higher capital cost, and there is no clear evidence of advantages regarding costs savings.

7. Discussion and comparison with other studies

There are not that many other studies reported in literature that address the factors limiting the adoption of robotics in the construction industry. Most of the studies only address the subject tangentially or focus on particular country-level conditions that affect adoption (e.g. Ref. [52]. However, to contribute to the discussion of this topic and evaluate the relevance of the findings of this study, the findings of the other two studies have been compared in this section. The studies are by Ref. [64]; which conducted a survey and interviews to identify and rank the 8 major barriers for adoption of robotics in the construction industries of Japan, Malaysia and Australia; and [16]; which presented a discussion on the challenges for the adoption of robotic in-situ fabrication. Table 6 presents a list of the identified factors by the three studies.

The most significant factors identified by Ref. [64] are the high cost of implementation and the fragmented nature of the construction industry. The least significant ones were unavailable technology and not accepted by the worker's unions [64]. and this study identified the high implementation costs as the highest ranked factor. However, the fragmented nature of the construction industry is ranked second by Ref. [64] and last by this study. There are essential differences in the methodologies of both studies, which can explain these differences. The main differences between [64] study and this study include: (a) this study used FGs and literature review to identify the potential factors instead of only literature review. (b) This study used FGs instead of individual interviews. FGs are more effective than individual interviews for exploratory research as participants can get inspiration and build upon arguments from others [19]. Thus, based on (i) and (ii), this study captured a broader and more complete set of up-to-date limiting factors.

On the other hand, the challenges discussed by Ref. [16] are based on the author's experience in developing robotic systems for the construction industry. Note that the challenges discussed are not ranked. Most of the discussion focuses on the technical challenges to develop a robotic system actually useable in the construction site complex conditions [16]. note that the way buildings are designed poses a great challenge to the adoption of robotics due to their low modularity, reusability, and information technology sophistication. Also, there are still many technical challenges including a lack of functional integration, ineffective localisation, planning, and guiding algorithms, inadequate sensor technology, insufficient robot intelligence, and the difficulty of robots to operate on complex and uncontrolled environments. Almost all of the identified factors by this study are discussed by Ref. [16]; this is another indication that the methodology used was effective in capturing the relevant factors.

The most important difference of this study and the other two studies compared here –and other studies in literature (e.g. Ref. [52]– is that this study in addition of identifying and ranking barriers for adoption, it also employed principal component analysis to define four categories that represent the underlying factors. This is a very relevant contribution as it facilitates understanding and devising appropriate plans of action to address the low levels of adoption. This study has distilled the myriad of factors limiting the adoption of robotics in the

Table 6

Limiting factors identified by this study and other studies in literature. Factors included in this study and [64] are in bold, factors included in this study and [16] are underlined, and factors present in the three studies are in bold and underlined.

Rank	This study	[64]	[16] [b]
1	**High initial capital investment**	**High implementation costs**	Design challenges (low modularity, reusability, and information technology sophistication)
2	No strong need to improve productivity	**Fragmented nature of the industry**	Immature technology (lack of functional integration, ineffective algorithms, robot intelligence, uncontrolled environments)
3	Low R&D budgets in the construction industry	Difficult to use	Lack of experts in the field
4	Current work culture/aversion to change	**High maintenance costs**[a]	Construction is a complex task
5	**Untrained workforce**	Incompatible with current workflows	Lack of clear business case/unproved effectiveness
6	Unproved effectiveness/immature technology	**Unskilled workforce**	Difficulty for new actors to enter the business
7	Easy access to labour	Unavailable technology	Fragmented nature of the industry
8	Low ROI/insufficient demand	Not accepted by workers unions	Low R&D and inexistent innovation ecosystem
9	Lack of government incentives		
10	Decreasing public infrastructure budgets		
11	**Fragmented nature of the construction industry**		

[a] This factor is included in high capital investment.

[b] The challenges identified by Ref. [16] are not ranked.

construction industry into four clear and understandable categories. This categorisation will help stakeholders to devise strategies to address various factors that share similar characteristics.

8. Implications for practice

The findings of this study have significant implications for construction companies, infrastructure owners, asset managers and planners, and policymakers. Potential actions to address the four categories discussed in section 6 are presented here.

Regarding contractor-side economic factors, the main priority should be to lower the level of risk in projects. If a new digital technology does not reduce risk, it does not represent a proper driver for uptake. On the contrary, the adoption of many new digital technologies represents an increase of risk, particularly to SMEs that do not have the financial stability to absorb new risks. This is very relevant as the majority of construction companies are SMEs. In addition, this study indicates that an increase in productivity is not a significant factor that can drive up adoption. Stakeholders should consider first how robotics can reduce risks for construction companies, which will justify the high initial capital investment.

Regarding client-side economic factors, governments as the biggest construction clients, have many tools at their disposal to incentivise the adoption of new technologies in the construction industry that range from fostering collaboration with academia and research institutes, economic incentives, additional provisions in contracts all the way to mandates. These tools have varying degrees of effectiveness and represent different levels of disruption. For example, voluntary programs for collaboration and economic incentives are not disruptive but may be too slow. On the other hand, mandates are very disruptive but can speed up adoption. The UK mandate for the use of BIM Level 2 for all public construction projects in 2016 caused great disruption and stress, but it demonstrated that client requirement is a significant driver for uptake [32]. Stakeholders should weight the benefits of the various approaches to drive uptake, considering the level of disruption and stress that they create.

Regarding technical and work culture factors, the major aspect that stakeholders should consider is the problems posed by human workers working alongside robots. Intensive collaboration with academia and research institutes is required to address this challenge. Note as well, that most of the research of robotics in construction has been focused on the development of new systems, but considerable efforts should be made on investigating the new of arising issues of the interaction between construction workers and robots.

Regarding the value that robotics can provide to the construction industry, this study shows that there are no sufficiently detailed cost/benefit studies for adopting robotics in construction. It is not enough to calculate the amount of time saved and the corresponding labour costs. These studies should include for example the costs for installation, accessories, maintenance, spare parts, training, energy, additional safety and health considerations, new facilities, inflation, deprecation, finance mechanisms, etc. Additionally, there are no studies that investigate the market capacity to absorb the demand for robotic-enabled construction. It is not clear whether the existing construction market structure and dynamics justify large capital investments in robotics.

Regarding theoretical implications, this study is one of the few studies that has focused on industry-specific challenges. More importantly, in contrast with other studies in which only anecdotical evidence is provided regarding challenges for adoption; the mixed research method used in this study provides significant evidence on where the main challenges reside. In general terms, the findings of this study align with existing knowledge. However, this study provides an additional level of analysis and understanding that will support the creation of effective mitigation strategies.

9. Conclusions and future work

Robotics has the potential to provide numerous advantages to the construction industry; however, the levels of adoption are very low. This paper presented a qualitative and quantitative study of the industry-specific challenges that limit the adoption of robotics in the construction industry. This study used a mixed research method to identify, categorise and rank the main factors limiting the adoption. The main identified challenges were grouped in four categories in order of importance: (1) Contractor-side economic factors, (2) Client-side economic factors, (3) Technical and work-culture factors, and (4) Weak business case factors. A reliability analysis was conducted to test the internal consistency of the identified factors; which indicated an acceptable internal consistency of the collected data. A correlation study was carried out, as well. No strong correlation was found among factors. A more detailed study on causality and secondary effects should be carried out to identify whether factors reinforce each other and can be addressed together or separately. This study helps stakeholders understand the main industry-specific factors limiting the adoption of robotics in the construction industry. The presented findings have substantial practical relevance as they can inform stakeholders on devising strategies to mitigate the identified factors. In addition, it is one of the first studies that presents significant evidence on where the main limitation factors for adopting robotics in the construction industry reside.

This study was carried out with companies with operations in Europe. While many of the big companies are transnational and have operations all over the world, other future studies should focus on investigating other parts of the world and comparing the results with this one. Such an approach would help to identify regional differences in levels of adoption and in the importance of the limitations. These types of studies will help to learn from best practices in different regions as well. Future work also includes a more granular study regarding the limitations and prospects for specific construction tasks. For example, a recent study in the UK shows that the main tasks that stakeholders would like to automate are: (1) concrete construction, (2) survey and monitoring, and (3) drilling, excavation and demolition [70]. In order to quicken adoption, specific strategies can be devised to address those specific tasks. Also, a study regarding how the adoption of other technologies (artificial intelligence, augmented reality, Internet of Things) can drive or limit the adoption should be carried out. The authors believe that synergies can be found and exploited among different technologies to fast forward the adoption of new technologies in the construction industry. Lastly, the impacts of robotics on the workforce must be investigated thoroughly. There is a common expectation that robotics and other technologies will substitute workers, but also provide comparative advantages [23]. These expectations must be studied in a systematic manner to ensure successful adoption and avoid major disruptions that can lead to unintended economic and social problems.

Acknowledgements

The authors would like to acknowledge and express their sincere gratitude to the Engineering and Physical Sciences Research Council (EPSRC) and Innovate UK (Grant Reference No. EP/N509012/1; Grant Application No. 44746-322224 / File No. 102061) for providing the financial support for this study.

References

[1] A. Ajoudani, A.M. Zanchettin, S. Ivaldi, A. Albu-Schäffer, K. Kosuge, O. Khatib, Progress and prospects of the human–robot collaboration, Aut. Robots 42 (2018) 957–975 https://doi.org/10.1007/s10514-017-9677-2.

[2] A.M. Alashwal, H.A. Rahman, A.M. Beksin, Knowledge sharing in a fragmented construction industry: on the hindsight, Sci. Res. Essays 6 (2011) 1530–1536 https://doi.org/10.5897/sre10.645.

[3] S. Allen, Why construction industry productivity is declining, Cambridge, MA, 1985. https://doi.org/10.3386/w1555.

[4] A. Alwasel, K. Elrayes, E. Abdel-Rahman, C. Haas, Reducing shoulder injuries among construction workers, ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction, 2012, pp. 1–5.

[5] H. Ardiny, S. Witwicki, F. Mondada, Construction automation with autonomous mobile robots: a review, 2015 3rd RSI International Conference on Robotics and Mechatronics (ICROM), IEEE, 2015, pp. 418–424 https://doi.org/10.1109/ICRoM.2015.7367821.

[6] K. Asadi, H. Ramshankar, H. Pullagurla, A. Bhandare, S. Shanbhag, P. Mehta, S. Kundu, K. Han, E. Lobaton, T. Wu, Vision-based integrated mobile robotic system for real-time applications in construction, Autom. ConStruct. 96 (2018) 470–482 https://doi.org/10.1016/J.AUTCON.2018.10.009.

[7] T. Bock, T. Linner, Robotic Industrialization : Automation and Robotic Technologies for Customized Component, Module, and Building Prefabrication, Cambridge University Press, 2016.

[8] T. Bock, T. Linner, Site Automation: Automated/Robotic On-Site Factories, Cambridge University Press, 2016.

[9] T. Bock, T. Linner, Construction Robots : Elementary Technologies and Single-Task Construction Robots, Cambridge University Press, 2017.

[10] T. Bock, T. Linner, W. Ikeda, Exoskeleton and humanoid robotic technology in construction and built environment, The Future of Humanoid Robots-Research and Applications, InTech, 2012.

[11] T. Bock, Construction robotics, Auton. Robots 22 (2007) 201–209 https://doi.org/10.1007/s10514-006-9008-5.

[12] T. Bock, The future of construction automation: technological disruption and the upcoming ubiquity of robotics, Autom. ConStruct. 59 (2015) 113–121 https://doi.org/10.1016/J.AUTCON.2015.07.022.

[13] R. Bogue, What are the prospects for robots in the construction industry? Ind. Robot An Int. J. 45 (2018) 1–6 https://doi.org/10.1108/IR-11-2017-0194.

[14] V. Braun, V. Clarke, Using thematic analysis in psychology, Qual. Res. Psychol. 3 (2006) 77–101 https://doi.org/10.1191/1478088706qp063oa.

[15] C. Brown, Autonomous vehicle technology in mining, Eng. Min. J. 213 (2012).

[16] J. Buchli, M. Giftthaler, N. Kumar, M. Lussi, T. Sandy, K. Dörfler, N. Hack, Digital in situ fabrication - challenges and opportunities for robotic in situ fabrication in architecture, construction, and beyond, Cement Concr. Res. 112 (2018) 66–75 https://doi.org/10.1016/J.CEMCONRES.2018.05.013.

[17] D. Castro-Lacouture, Construction automation, Springer Handbook of Automation, Springer Berlin Heidelberg, Berlin, Heidelberg, 2009, pp. 1063–1078 https://doi.org/10.1007/978-3-540-78831-7_61.

[18] B. Chen, H. Ma, L.-Y. Qin, F. Gao, K.-M. Chan, S.-W. Law, W.-H. Liao, Recent developments and challenges of lower extremity exoskeletons, J. Orthop. Transl. 5 (2016) 26–37 https://doi.org/10.1016/J.JOT.2015.09.007.

[19] J. Creswell, Research Design: Qualitative, Quantitative, and Mixed Methods Approaches, Sage Publications, 2017.

[20] J. Czarnowski, A. Dąbrowski, M. Maciaś, J. Główka, J. Wrona, Technology gaps in Human-Machine Interfaces for autonomous construction robots, Autom. ConStruct. 94 (2018) 179–190 https://doi.org/10.1016/J.AUTCON.2018.06.014.

[21] S. Dadhich, U. Bodin, U. Andersson, Key challenges in automation of earth-moving machines, Autom. ConStruct. 68 (2016) 212–222 https://doi.org/10.1016/J.AUTCON.2016.05.009.

[22] S. Dadhich, A Survey in Automation of Earth-Moving Machines, Luleå tekniska universitet, 2015.

[23] H. David, Why are there still so many jobs? The history and future of workplace automation, J. Econ. Perspect. 29 (2015) 3–30 https://doi.org/10.1257/jep.29.3.3.

[24] J.M. Davila Delgado, L.J. Butler, N. Gibbons, I. Brilakis, M.Z.E.B. Elshafie, C. Middleton, Management of structural monitoring data of bridges using BIM, Proc. Inst. Civ. Eng. - Bridg. Eng. 170 (2017) 204–218 https://doi.org/10.1680/jbren.16.00013.

[25] J.M. Davila Delgado, L.J. Butler, I. Brilakis, M.Z.E.B. Elshafie, C.R. Middleton, Structural performance monitoring using a dynamic data-driven BIM environment, J. Comput. Civ. Eng. 32 (2018).

[26] J.M. Davila Delgado, L. Oyedele, M. Bilal, A. Ajayi, A. Akanbi, O. Akinade, Big Data analytics system for costing power transmission projects, J. Constr. Eng. Manag. (2019) In press http://eprints.uwe.ac.uk/41073 , Accepted version:.

[27] M.P. de Looze, T. Bosch, F. Krause, K.S. Stadler, L.W. O'Sullivan, Exoskeletons for industrial application and their potential effects on physical work load, Ergonomics 59 (2016) 671–681 https://doi.org/10.1080/00140139.2015.1081988.

[28] D. Delgado Camacho, P. Clayton, W.J. O'Brien, C. Seepersad, M. Juenger, R. Ferron, S. Salamone, Applications of additive manufacturing in the construction industry – a forward-looking review, Autom. ConStruct. 89 (2018) 110–119 https://doi.org/10.1016/J.AUTCON.2017.12.031.

[29] G. Di Stefano, G. Romeo, A. Mazzini, A. Iarocci, S. Hadi, S. Pelphrey, The Lusi drone: a multidisciplinary tool to access extreme environments, Mar. Pet. Geol. 90 (2018) 26–37 https://doi.org/10.1016/J.MARPETGEO.2017.07.006.

[30] K. Dörfler, T. Sandy, M. Giftthaler, F. Gramazio, M. Kohler, J. Buchli, Mobile robotic brickwork, Robotic Fabrication in Architecture, Art and Design 2016, Springer International Publishing, Cham, 2016, pp. 204–217 https://doi.org/10.1007/978-3-319-26378-6_15.

[31] S. Dritsas, G.S. Soh, Building robotics design for construction, Constr. Robot. (2018) 1–10 https://doi.org/10.1007/s41693-018-0010-1.

[32] R. Eadie, M. Browne, H. Odeyinka, C. McKeown, S. McNiff, A survey of current status of and perceived changes required for BIM adoption in the UK, Built. Environ. Proj. Asset. Manag. 5 (2015) 4–21 https://doi.org/10.1108/BEPAM-07-2013-0023.

[33] K. El-Abidi, F. Ghazali, Motivations and limitations of prefabricated building: an overview, Appl. Mech. Mater. 802 (2015) 668–675.

[34] European Investment Bank, EIB Investment Report 2017/2018, (2017).

[35] J. Farley, B. Kabn, D. Lebmann, W. Moore, Modeling the choice to automate, Sloan Manag. Rev. 28 (1987).

[36] M.D. Fetters, L.A. Curry, J.W. Creswell, Achieving integration in mixed methods designs-principles and practices, Health Serv. Res. 48 (2013) 2134–2156 https://doi.org/10.1111/1475-6773.12117.

[37] L.H. Forbes, S.M. Ahmed, Modern Construction : Lean Project Delivery and Integrated Practices, CRC Press, 2011.

[38] B. García de Soto, I. Agustí-Juan, J. Hunhevicz, S. Joss, K. Graser, G. Habert, B.T. Adey, Productivity of digital fabrication in construction: cost and time analysis of a robotically built wall, Autom. ConStruct. 92 (2018) 297–311 https://doi.org/10.1016/J.AUTCON.2018.04.004.

[39] V. Gerling, S. Von Mammen, Robotics for self-organised construction, 2016 IEEE 1st International Workshops on Foundations and Applications of Self* Systems (FAS*W), IEEE, 2016, pp. 162–167 https://doi.org/10.1109/FAS-W.2016.45.

[40] S. Goessens, C. Mueller, P. Latteur, Feasibility study for drone-based masonry construction of real-scale structures, Autom. ConStruct. 94 (2018) 458–480 https://doi.org/10.1016/J.AUTCON.2018.06.015.

[41] S. Gupta, A. Agrawal, E. Singla, Wearable Upper Limb Exoskeletons: Generations, Design Challenges and Task Oriented Synthesis, Springer, Cham, 2019, pp. 134–142 https://doi.org/10.1007/978-3-030-00329-6_16.

[42] J. Hair, W. Black, B. Babin, R. Anderson, Multivariate Data Analysis, seventh ed., Pearson, 2010.

[43] K. Hampson, P. Newton, Transforming the built environment through construction innovation, Technology, Design and Process Innovation in the Built Environment, Spoon Press, 2009, pp. 29–54.

[44] K.D. Hampson, J.A. Kraatz, A. Sanchez, The global construction industry and R&D, R&D Investment in the Global Construction Industry, 2014, pp. 1–16.

[45] J. Hendricks, Applying cost accounting to factory automation, Manag. Account. 70 (1988).

[46] W. Hölzl, M. Böheim, M. Klien, E. Pichler, Public procurement and the tension between the economically most advantageous tender and lowest price, WIFO Stud (2017).

[47] P.Y. Huang, M. Sakurai, Factory automation: the Japanese experience, IEEE Trans. Eng. Manag. 37 (1990) 102–108 https://doi.org/10.1109/17.53712.

[48] L. Jaillon, C.S. Poon, The evolution of prefabricated residential building systems in Hong Kong: a review of the public and the private sector, Autom. ConStruct. 18 (2009) 239–248 https://doi.org/10.1016/J.AUTCON.2008.09.002.

[49] A. Jayaraj, H.N. Divakar, Robotics in construction industry, IOP Conf. Ser. Mater. Sci. Eng. 376 (2018) 012114 https://doi.org/10.1088/1757-899X/376/1/012114.

[50] JFCC, Construction Industry Handbook 2012, (2012) (Tokyo).

[51] J.O. Jonassen, Report on Integrated Practice, Changing business models in BIM-driven integrated practice (2010).

[52] K. Kamar, M. Azman, M. Nawi, K.A. Kamar, M.N. Azman, M.N. Nawi, IBS survey 2010: drivers, barriers and the critical success factors in adopting industrialised building system (IBS) construction by G7 contractors in Malaysia, J. Eng. Sci. Technol. 9 (2014) 490–501.

[53] C. Kasperzyk, M.-K. Kim, I. Brilakis, Automated re-prefabrication system for buildings using robotics, Autom. ConStruct. 83 (2017) 184–195 https://doi.org/10.1016/J.AUTCON.2017.08.002.

[54] M. Kim, H. Chi, X. Wang, L. Ding, Automation and robotics in construction and civil engineering, J. Intell. Robot. Syst. 79 (2015).

[55] S. Kim, A. Moore, D. Srinivasan, A. Akanmu, A. Barr, C. Harris-Adamson, D.M. Rempel, M.A. Nussbaum, Potential of exoskeleton technologies to enhance safety, health, and performance in construction: industry perspectives and future research directions, IISE Trans. Occup. Ergon. Hum. Factors 1–7 (2019), https://doi.org/10.1080/24725838.2018.1561557.

[56] N. Koyachi, S. Sarata, Unmanned loading operation by autonomous wheel loader, 2009 ICCAS-SICE, 2009 ([publisher not identified], p. r).

[57] V.S.S. Kumar, I. Prasanthi, A. Leena, Robotics and automation in construction industry, AEI 2008, American Society of Civil Engineers, Reston, VA, 2008, pp. 1–9 https://doi.org/10.1061/41002(328)3.

[58] S. Lee, W. Pan, T. Linner, T. Bock, A framework for robot assisted deconstruction: process, sub-systems and modelling, Proceedings of the 32nd ISARC, 2015, pp. 1–8 https://doi.org/10.22260/ISARC2015/0093.

[59] Y. Li, C. Liu, Applications of multirotor drone technologies in construction management, Int. J. Constr. Manag. 1–12 (2018), https://doi.org/10.1080/15623599.2018.1452101.

[60] R. Li, Robots for the construction industry, An Economic Analysis on Automated Construction Safety, Springer, 2018, pp. 23–46.

[61] S. Lim, R.A. Buswell, T.T. Le, S.A. Austin, A.G.F. Gibb, T. Thorpe, Developments in construction-scale additive manufacturing processes, Autom. ConStruct. 21 (2012) 262–268 https://doi.org/10.1016/J.AUTCON.2011.06.010.

[62] T. Linner, T. Bock, Evolution of large- scale industrialisation and service innovation in Japanese prefabrication industry, Constr. Innovat. 12 (2012) 158–178 https://doi.org/10.1108/14714171211215921.

[63] M. Loosemore, J. Richard, Valuing innovation in construction and infrastructure: getting clients past a lowest price mentality, Eng. Construct. Architect. Manag. 22 (2015) 38–53 https://doi.org/10.1108/ECAM-02-2014-0031.

[64] R. Mahbub, An Investigation into the Barriers to the Implementation of Automation and Robotics Technologies in the Construction Industry, Queensland University of Technology, 2008.

[65] K. Manley, J. Marceau, R. Parker, J. Matthews, The Potential Contribution of Small Firms to Innovation in the Built Environment, (2008).

[66] F. Marley, Exploring the Impact of the Ageing Population on the Workforce and Built Environment - CIOB Policy, (2015).

[67] B.Y. McCabe, H. Hamledari, A. Shahi, P. Zangeneh, E.R. Azar, Roles, benefits, and challenges of using UAVs for indoor smart construction applications, Computing in

Civil Engineering 2017, American Society of Civil Engineers, Reston, VA, 2017, pp. 349–357 https://doi.org/10.1061/9780784480830.043.

[68] M. Miozzo, P. Dewick, Networks and innovation in European construction: benefits from inter-organisational cooperation in a fragmented industry, Int. J. Technol. Manag. 27 (2004) 68 https://doi.org/10.1504/IJTM.2004.003882.

[69] A. Mirjan, F. Augugliaro, R. D'Andrea, F. Gramazio, M. Kohler, Building a bridge with flying robots, Robotic Fabrication in Architecture, Art and Design 2016, Springer International Publishing, Cham, 2016, pp. 34–47 https://doi.org/10.1007/978-3-319-26378-6_3.

[70] MTC, i3P Discovery Programme: Robotics and Automation, (2017).

[71] J.C. Nunnally, I.H. Bernstein, Psychometric Theory, McGraw-Hill, 1994.

[72] T.D. Oesterreich, F. Teuteberg, Understanding the implications of digitisation and automation in the context of Industry 4.0: a triangulation approach and elements of a research agenda for the construction industry, Comput. Ind. 83 (2016) 121–139 https://doi.org/10.1016/J.COMPIND.2016.09.006.

[73] M. Pan, T. Linner, W. Pan, H. Cheng, T. Bock, A framework of indicators for assessing construction automation and robotics in the sustainability context, J. Clean. Prod. 182 (2018) 82–95 https://doi.org/10.1016/J.JCLEPRO.2018.02.053.

[74] J. Pecoraro, C. Harper, C. Wang, Unmanned aircraft systems in constructionand agriculture: uses, benefits, challenges, and why companies choose to invest, KICEM J. Constr. Proj. Manag. 7 (2017) 34–44.

[75] H. Peel, S. Luo, A.G. Cohn, R. Fuentes, Localisation of a mobile robot for bridge bearing inspection, Autom. ConStruct. 94 (2018) 244–256 https://doi.org/10.1016/J.AUTCON.2018.07.003.

[76] I. Perkins, M. Skitmore, Three-dimensional printing in the construction industry: a review, Int. J. Constr. Manag. 15 (2015) 1–9 https://doi.org/10.1080/15623599.2015.1012136.

[77] V.R. Prasath Kumar, M. Balasubramanian, S. Jagadish Raj, Robotics in construction industry, Indian J. Sci. Technol. 9 (2016), https://doi.org/10.17485/ijst/2016/v9i23/95974.

[78] T. Rakha, A. Gorodetsky, Review of Unmanned Aerial System (UAS) applications in the built environment: towards automated building inspection procedures using drones, Autom. ConStruct. 93 (2018) 252–264 https://doi.org/10.1016/J.AUTCON.2018.05.002.

[79] S.J. Ray, J. Teizer, Real-time construction worker posture analysis for ergonomics training, Adv. Eng. Inf. 26 (2012) 439–455 https://doi.org/10.1016/J.AEI.2012.02.011.

[80] E.M. Rojas, P. Aramvareekul, Labor productivity drivers and opportunities in the construction industry, J. Manag. Eng. 19 (2003) 78–82 2003)19:2(78 https://doi.org/10.1061/(ASCE)0742-597X.

[81] M. Sahin-Dikmen, L. Clarke, Disparities in Labour and VET in meeting LEC targets, ILPC 2017, 2017.

[82] J. Sauder, E. Hilgemann, B. Bienstock, A. Parness, An automaton rover enabling long duration in-situ science in extreme environments, 2017 IEEE Aerospace Conference, IEEE, 2017, pp. 1–10 https://doi.org/10.1109/AERO.2017.7943829.

[83] J.P. Sousa, C.G. Palop, E. Moreira, A.M. Pinto, J. Lima, P. Costa, P. Costa, G. Veiga, A. Paulo Moreira, The SPIDERobot: a cable-robot system for on-site construction in architecture, Robotic Fabrication in Architecture, Art and Design 2016, Springer International Publishing, Cham, 2016, pp. 230–239 https://doi.org/10.1007/978-3-319-26378-6_17.

[84] P. Stilger, J. Siderius, E. van Raaij, A comparative study of formulas for choosing the economically most advantageous tender, J. Public Procure. 17 (2017) 89–125 https://doi.org/10.1108/JOPP-17-01-2017-B004.

[85] Y.W.D. Tay, B. Panda, S.C. Paul, N.A. Noor Mohamed, M.J. Tan, K.F. Leong, 3D printing trends in building and construction industry: a review, Virtual Phys. Prototyp. 12 (2017) 261–276 https://doi.org/10.1080/17452759.2017.1326724.

[86] P. Vähä, T. Heikkilä, P. Kilpeläinen, M. Järviluoma, E. Gambao, Extending automation of building construction — survey on potential sensor technologies and robotic applications, Autom. ConStruct. 36 (2013) 168–178 https://doi.org/10.1016/J.AUTCON.2013.08.002.

[87] A. van Marrewijk, M. Veenswijk, S. Clegg, Changing collaborative practices through cultural interventions, Build. Res. Inf. 42 (2014) 330–342 https://doi.org/10.1080/09613218.2014.867619.

[88] J. Watson, G. Sharp, Barriers to skills development in a local construction labour market, Local Econ. 22 (2007) 123–137 https://doi.org/10.1080/02690940701394205.

[89] A. Więckowski, “JA-WA” - a wall construction system using unilateral material application with a mobile robot, Autom. ConStruct. 83 (2017) 19–28 https://doi.org/10.1016/J.AUTCON.2017.02.005.

[90] C. Wong, E. Yang, X.-T. Yan, D. Gu, Autonomous robots for harsh environments: a holistic overview of current solutions and ongoing challenges, Syst. Sci. Control Eng. 6 (2018) 213–219 https://doi.org/10.1080/21642583.2018.1477634.

[91] P. Wu, J. Wang, X. Wang, A critical review of the use of 3-D printing in the construction industry, Autom. ConStruct. 68 (2016) 21–31 https://doi.org/10.1016/J.AUTCON.2016.04.005.

[92] G. Yang, J. Bellingham, P. Dupont, F. P, L. Floridi, The grand challenges of Science Robotics, Sci. Robot 3 (2018).

[93] S. You, J.-H. Kim, S. Lee, V. Kamat, L.P. Robert, Enhancing perceived safety in human–robot collaborative construction using immersive virtual environments, Autom. ConStruct. 96 (2018) 161–170 https://doi.org/10.1016/J.AUTCON.2018.09.008.

[94] X. Zhang, M. Li, J.H. Lim, Y. Weng, Y.W.D. Tay, H. Pham, Q.-C. Pham, Large-scale 3D printing by a team of mobile robots, Autom. ConStruct. 95 (2018) 98–106 https://doi.org/10.1016/J.AUTCON.2018.08.004.