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Research article

The potential of construction robotics to reduce airborne virus transmission in the construction industry in the UK and China

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ABSTRACT

This paper aims to identify construction robotics' potential to reduce airborne virus transmission, review factors limiting the technology's adoption and highlight how similar barriers have been addressed in other industries. Construction robotics were identified and classified into 8 themes with 25 categories through a critical literature review. We undertook interviews with 4 construction contractors and conducted an online questionnaire with 32 experts from the UK (n = 14) and China (n = 18) who reviewed the robotic systems we identified and ranked the potential ability of each to reduce airborne virus transmission within the construction industry. The results of this study showed that construction robotics is not only beneficial to reduce airborne virus transmission, but may also help to reduce the spread of future contagious viruses. We found no significant difference (P>0.05) in practical usage and implementation barriers to construction robotics between the UK and China. Cost, training and limited awareness of robotic technologies were the main implementation barriers we identified in both countries. Both the UK and China may need to adopt strategies such as providing more financial support to small construction industries and skill training which are utilised successfully in other sectors to realise the potential of construction robotic technologies.

1. Introduction

Since the first adoption of construction robotics in the 1970s in Japan [1,2], research into construction automation or robotics rapidly increased to improve productivity in both on-site and off-site construction activities [3]. Bock [4] in 2015 postulated that to meet the growing demands of the construction industry, traditional methods of construction have reached their limits and the ubiquity of robotics would be the development trend. In addition, studies have identified that construction robotics has great potential to increase efficiency and productivity and thus combat a reduction in labour availability [3,5–9]. For example, Tybot and Brayman Construction have successfully developed a rebar-tying robot that resulted in a 40% reduction in labour hours and a 30-day schedule reduction during the construction of a bridge deck project in 2018 [10]. In 2020, Gharbia et al. [3] also highlighted that construction robotics and automated systems have been adopted to undertake repetitive, dirty and dangerous activities, preventing workers

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from being exposed to risks from hazardous environments and increasing productivity. Additionally, in 2022, Iturralde et al. [11] highlighted the higher accuracy and shorter installation time of construction robotics through a case study with a cable-driven parallel robot for curtain wall installation. These findings are supported by other literature [3,12,13].

Since the 1960's adoption of robotics has been slow in comparison to other industries due to factors which include high capital costs and an unwillingness to change current working practices [3,14–19]. A comprehensive literature review conducted by Cai et al. [20] in 2019 explored existing technologies used in high-rise building activities and compared construction robotics development within academia and industry. This research found that whilst there was significant academic development of robotic and automated systems for construction this did not translate to significant commercialisation of technology, with only 105 companies providing commercial construction robotics up to 2019. The UK government 2021 report 'The Economic Impact of Robotics & Autonomous Systems Across UK Sector' concluded that the current robot density in construction was the lowest (<0.1 robotics per million hours worked) compared with 6 other sectors, agriculture, health and social care, energy, food and drink, infrastructure and logistics sectors [21]. However, there is a significant need to increase the productivity of the construction industry as it faces several challenges [3,5,19,22–25]. A survey from Mckinsey Global Institute (MGI) in 2017 [26] determined that construction labour productivity has not increased and may even have declined over the last decades [27–29].

Since the 1970s, the major barriers to construction robotics adoption were identified in previous studies [30–33], and have been stated as financial difficulties, insufficient development of technology and managerial barriers. However, recent studies showed that financial difficulties (e.g. high investment cost and limited financial support from the government), requirements of highly skilled/qualified operators and complexity of the supply chain are still the main implementation barriers of construction robotics [16,20,34]. The adoption of robotics in the construction industry could partially alleviate the problems related to low productivity and project progress. Especially, during COVID-19, there was a large loss of life, high rates of unemployment and economic recession in many countries globally [35–38].

According to the UK Department of Trade and Industry's Review of Early Estimates of Construction Output for Gross Domestic Product (GDP) report [39], the construction industry accounts for 5.4% of the UK's GDP making it a crucial sector of the UK's economy. The Construction News website in 2020 reported, that the cost of project delays in the UK, due to the impacts of COVID-19 was estimated at £104 billion [40]. According to the Office for National Statistics (ONS) Construction Output in Great Britain: April 2020 report, the total output value of the construction industry in the UK fell by 40.1% from the previous month, due to a 41.2% decrease in new projects beginning and a 38.1% decrease in maintenance-related construction activities [41]. Certification and Risk Management Organization (CHAS) news reported that due to the pandemic, the turnover of UK construction companies fell by more than 70%, and nearly 80% of activities in the construction industry and its supply chain were delayed or adversely affected [42]. In 2020, the University of Wolverhampton conducted semi-structured interviews with 13 construction professionals from 10 companies in the UK. All participants stated their employers had significant issues related to shrinkage and cash flow due to COVID-19 [43], which also supported the findings from CHAS. Concerning the impact of the pandemic in China, the lockdown halted construction activities and caused a 10 million Chinese Yuan loss of capital investment in the construction sector in 2020 [44]. In 2021, Liu [45] determined that during the first quarter of 2020 in China, the overall economic output was the worst since 1992, and production in the construction sector reduced by 17.5%.

The main research question for this study is that if construction industries could cope better with airborne viruses such as COVID-19 if they adopted construction robotics. To answer this question, the United Kingdom (UK) and China were selected as examples of developed and developing countries according to the Organisation for Economic Co-operation and Development (OECD), respectively in this study.

Based on current research, we propose that using appropriate technologies, such as robotics, may be an effective way to reduce the spread of airborne viruses, such as COVID-19 in the construction industry and enable activities to continue safely. However, the level of adoption of robotics for construction in both the UK and China is relatively low, both are less than 1% [21,46]. Although many studies identified the implementation barriers of construction robotics [15,16,34,47,48], none of them have considered successful strategies which have been used in other industries to solve these challenges.

Building on our research with the UK Health and Safety Executive and Tomas Ashton Institute, published as 'Keeping the UK Building Safely: a scoping study: Prepared for: The PROTECT COVID-19 National Core Study on transmission and environment' [49], we have undertaken a further investigation of the potential benefits of construction robotics at reducing the spread of contagious viruses such as COVID-19 and potential strategies to overcome the implementation barriers. If this is found to be beneficial then to realise this a wider adoption of robotic systems within the industry would be needed. We are unaware of existing research that considers this research question.

1.1. Research questions and aims

The research questions of this study can be summarised as follows:

- Could the construction industry continue to operate safely during a contagious virus pandemic, such as COVID-19, through greater usage of construction robotic technology?
- What are the current and perceived benefits and barriers to the adoption of robotics within the construction industry in Developed (UK) and Developing (China) countries and have they changed since the 1970s?
- How can construction industries overcome implementation barriers and increase robotics adoption in Developed (UK) and Developing (China) countries?

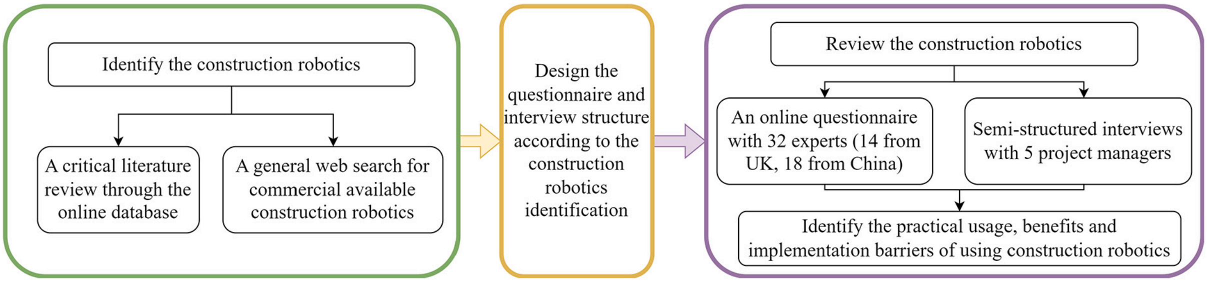

Fig. 1. Flowchart of overall methodology.

This study aims to answer the research questions through a critical literature review, an online questionnaire and interviews with stakeholders. The main contribution of this study is first, the potential of construction robotics to minimise the risk of virus transmission and maintain productivity was identified and ranked; secondly, the potential solutions to overcome construction robotics implementation barriers were identified and discussed.

The structure of this paper is as follows: In Section 2, the research methodology is presented. Then, in section 3, construction robots are identified, classified and discussed through a scoping literature review. Furthermore, Section 3 investigates the potential of using construction robotics as a technology shield to keep the construction industry safe and maintain productivity in the UK and China during airborne viruses through an online questionnaire with experts. The potential and challenges of construction robotics adoption are discussed in Section 4, with suggested strategies to increase construction robotics adoption highlighted. Section 5 summarises the research conclusions and proposes future research directions.

2. Methodology

The overall methodology of this study is illustrated in Fig. 1. A comprehensive literature review was undertaken to ascertain the existing landscape of construction robotics to assess their commercial viability. Subsequently, guided by the outcomes of the literature review, an online questionnaire and semi-structured interviews were formulated and administered among construction professionals.

2.1. Critical literature review of construction robotics

To identify the latest developments in construction robotics, a critical literature review on current review papers was conducted in Web of Science and Scopus databases. The keywords used for the literature research were related to construction robotic systems, specifically (‘Robot’ OR ‘Robotic’) AND (‘Construction’).

The titles, abstract, and then full texts were screened for papers that met the following inclusion criteria:

1. Written in English
2. Published from 1st January 1985 to 31st December 2022
3. Related to robotics/automation systems including collaborative robot and human-robot collaboration/interaction in the construction sector
4. Additional relevant papers identified from screening references of selected review papers

The exclusion criteria were:

1. Not written in English
2. Describing AI influence, control strategies and surgical robots

The papers identified through the critical literature review were analysed to identify construction robotic systems which were classified and categorised according to their working environment/location/position. The main aim was to figure out the implementation of construction robotics and their potential to maintain safe operations in the industry during airborne virus (e.g. COVID-19), we focus on commercialised construction robotics utilised within the industry. To achieve this, we did a further search of the web, using the following steps:

1. An internet search was conducted using Google to determine which of the robotics systems identified from the literature review have been commercialised. The robot name and type were used as search keywords.
2. A further general internet search was conducted to identify additional commercialised robotic systems based on keywords such as ‘construction robot’ and ‘commercial’ using Google.
3. The details (e.g. robot objective, control strategy, features and requirements for the operator) of commercialised and plan for commercialised construction robotics were identified and summarised.

2.2. Questionnaire and interviews with construction industry experts regarding the potential of robotics to reduce airborne virus transmission

2.2.1. Online questionnaire

Following the literature review, an online questionnaire was conducted from May 2021 to March 2022 through the online survey software Qualtrics (US, Appendix 1) to identify the potential ability of construction robotics to reduce airborne virus transmission, practical usage and implementation barriers in the UK and China. The questions in the questionnaire were identified and developed through the focus group among authors. To guarantee the online questionnaire works properly, a pilot survey was conducted among the authors before it was published. The questionnaire was distributed through professional networks (email), and social media (LinkedIn, Twitter) targeting experts in the civil engineering and construction industry. According to the guidance of Hallowell and Gambastese [50] and previous research [51–53], we defined 'experts' as having more than 5 years of work experience in this research. Guest et al. [54] in their research 'How many interviews are enough? An experiment with data saturation and variability states that a minimum of 8 experts is needed to obtain a reliable, representative view, we therefore set this as a minimum target. We captured data on the experts' backgrounds, and experience, to determine their expertise and opinions on the use of construction robotics. Participants were also asked to rank the construction robotics we identified through the literature review according to 1) the potential to increase the social distance between workers undertaking the same activity conventionally; 2) the potential to reduce the number of workers required to undertake the activity; 3) the potential to conduct the same activity remotely; 4) the potential to reduce the time taken to complete the activity (hence reducing potential exposure). Experts were asked to evaluate each robotic technology according to these four questions rating from 'Not at all' (0) to 'Very high' (4). There was a further option for the participants to opt out of answering questions they did not feel they had the expertise or experience to comment on. The median response, which is more robust to outliers was determined for each question applied to each robotic system.

2.2.2. Interviews with 4 United Kingdom construction industry contractors

Semi-interviews were conducted parallel to obtain more comprehensive results. Five project managers from four of the top 20 construction industry contractors in the UK were interviewed through an online communication platform, Zoom. All participants were asked to be anonymous and no private data was collected. The interviews aimed to identify the practical usage of construction robotics and stakeholders' attitudes to the adoption of construction robotics.

Questions were asked during the interview as follows:

• Have you used any type of technology to reduce the transmission of airborne viruses in your industry? If not, could you please provide the reason?

• Will you choose to use any technology such as construction robotics in your industry? Could you please provide the reason?

2.2.3. Data analysis and ethical approval for research

IBM SPSS (Statistical Package for the Social Sciences) V25.0 was used for all quantitative data analysis collected through online questionnaires, including the usage and implementation barriers of construction robotics and the potential ability to use construction robotics to reduce the transmission of airborne viruses in both the UK and China. Analysis of variance (ANOVA) was used for the comparison between different countries.

Qualitative content analysis was used to analyse all qualitative data, which were collected from both online questionnaires and interviews. The collected data was categorised into three main themes: 1-The background of participants; 2-The experience and willingness to use construction robotics; 3-The perceived benefits of construction robotics; 4-The perceived implementation barriers of construction robots.

3. Results

3.1. Identified construction robotics

In total 7291 papers were identified from Scopus (n = 7027) and Web of Science (n = 264) database. Fig. 2 illustrates the study selection of the literature review. After eliminating duplicate entries (n = 18), excluding studies deemed irrelevant during title (n = 7122) and abstract (n = 119) screening, removing articles that do not focus on robotics (n = 13), and incorporating additional pertinent articles identified through the reference screening of eligible studies (n = 7), a total of 26 studies were deemed suitable for inclusion in the final review [2,3,20,25,55–76].

There is no universally agreed approach for classifying construction robotics within the existing body of knowledge, owing to variations in the definition of construction robotics. Therefore, we have classified commercially available construction robotic systems into 8 themes based on the work environments within which they operate to improve clarity. The 8 adopted themes are as follows:

(1) Multiple sites construction robots (these are robots that can be used within different environments); (2) Indoor construction robots (these robots are mostly used for indoor environments); (3) Outdoor construction robots (these robots are mostly used for outdoor environments); (4) Aerial building and survey construction robot (these are all types of aerial robots); (5) Roof construction robot (these robots are mostly used for roof construction tasks); (6) Off-site construction robot; (7) Facade construction robot (these robots are mostly used for façade work, e.g. façade cleaning and painting); (8) Underground construction robot (these robots are mostly used for underground or foundation environments), see Fig. 3.

After conducting the internet search, 24 commercialised robotic systems were identified and summarised, as shown in Table 1. The Technology Readiness Level (TRL) for the systems presented in Table 1 was between TRL8 to TRL9; that is to say, they were commercialised either as a service provided by a 3rd party to the construction industry or as a commercial system which can be purchased for use on-site [77]. The general advantages and disadvantages of each identified construction robotic system are presented in Table 1. High accuracy, high-intensity work and high work efficiency were the common advantages of commercialised construction robotics. The high cost of robotics and the high requirement for skilled operators and training were the general disadvantages for most commercialised construction robotics, which are also the implementation barriers for construction robotics.

Table 1
Most used or representative system for each theme of construction robots.

Source&Year [Ref]	Classification	Objective	Features
Balzan et al. 2020 [75]	Theme 4, Category 4-2	Construction site monitoring and supervision	**Advantages:** 1. Increased surveying speed 2. Reduce risks of people surveying dangerous environments 3. Lower cost than light aircraft/helicopter alternatives **Control:** Teleoperated **Disadvantages:** 1. Require skilled operators 2. High initial capital investment in equipment 3. Depending on suitable weather conditions 4. Distract construction workers [64]
Guillen 2021 [78]	Theme 3, Category 3-2	Construction site monitoring and supervision	**Advantages:** 1. High accurate navigation **Control:** Teleoperated **Disadvantages:** 1. Require skilled operators 2. Complicate data collection process
Madsen 2019 [79]	Theme 3, Category 3-1	Brick laying	**Advantages:** 1. Reduce manual lifting 2. Significant reduction in labour costs 3. 3 to 5-fold increase in productivity 4. High precision 5. Real-time production data **Control:** Semi-autonomous **Disadvantages:** 1. Bricks and mortar need to be manually loaded 2. Optimum efficiency only realised through large-scale projects 3. Large capital investment in equipment 4. Increased set-up time on some occasions
Pessoa et al. 2021 [80]	Theme 3, Category 3-3	Print building	**Advantages:** 1. Construction of irregularly shaped structures 2. Reduction of construction waste 3. Easily transported **Control:** Fully autonomous **Disadvantages:** Low production speed
Taylor et al. 2003 [81]	Theme 2, Category 2-4	Floor finishing	**Advantages:** 1. Low-cost 2. High accuracy and concrete trowel speed 3. Lighter weight compared with similar products 4. High work efficiency **Control:** Teleoperated **Disadvantages:** Require skilled operators
Lin and Luo 2015 [55]	Theme 1, Category 1-2	Steel welding	**Advantages:** 1. Reduction in human labour requirements 2. High quality and precise welds **Control:** Fully autonomous **Disadvantages:** Difficult for transportation
Zhao et al. 2022 [76]	Theme 2, Category 2-2	Concrete distribution	**Advantages:** 1. Reduction in human labour requirements 2. Remote control **Control:** Fully autonomous **Disadvantages:** Require skilled operators
Liu et al. 2018 [82]	Theme 2, Category 2-6	Floor tiling	**Advantages:** 1. Reduce labour requirements 2. Increase speed of concrete distribution **Control:** Fully autonomous **Disadvantages:** Require skilled operators
Balzan et al. 2020 [75]	Theme 1, Category 1-5	Automated delivery of construction materials on-site	**Advantages:** 1. Ensure timely delivery of construction materials on-site 2. Increase productivity through timely delivery of materials 3. Reduce manual lifting therefore reduce occupational health hazard **Control:** Fully autonomous **Disadvantages:** Large size and require more pre-assemble time
Reichenbach 2021 [83]	Theme 2, Category 2-3	Concrete levelling and compaction	**Advantages:** 1. Compact–easy to deploy 2. High level of flatness **Control:** Fully autonomous **Disadvantages:** Require workers to clean the concrete corners
Kochan 2005 [84]	Theme 7, Category 7-1	Roof glass cleaning	**Advantages:** 1. Reduction in human labour requirements 2. Increase cleaning speed **Control:** Teleoperated **Disadvantages:** Movement is limited by ambilocal cable
Invert Robotics 2021 [85]	Theme 7, Category 7-1	Surface inspection of facade	**Advantages:** 1. Excellent climbing ability on various surfaces 2. Multiple methods of detection capabilities 3. Can work continuously 24/7 **Control:** Teleoperated **Disadvantages:** Require skilled operators
Anudari 2019 [86]	Theme 7, Category 7-1	Facade painting	**Advantages:** 1. Multitasks-oriented design 2. Reduce risks to workers 3. Workers will not be exposed to harmful paint substances 4. Constant outcome quality **Control:** Fully autonomous with teleoperation capability **Disadvantages:** 1. Can only move up and down. Reinstallation is required to move left and right. 2. Limited by weather conditions
Bogue 2018 [87]	Theme 7, Category 7-1	Reduce labour needs	**Advantages:** 1. Simplify installation process 2. High efficiency 3. Reduce manual lifting **Control:** Teleoperated **Disadvantages:** Require high accuracy of installation position
Bock 2015 [4]	Theme 6	Assembly building modules	**Advantages:** 1. Increased building quality of construction components 2. Reduce the construction time 3. Effectively controls pollution **Control:** Fully autonomous **Disadvantages:** 1. high transportation cost 2. Higher cost for plant construction
Tay et al. 2017 [59]	Theme 6	Binder jet printing the whole irregular structures	**Advantages:** 1. Enables manufacture of complex geometry shapes 2. Almost zero emissions/ Effectively control pollution 3. Easily control of detailing and finish of structure **Control:** Fully autonomous **Disadvantages:** Affected by bad weather
Branch Technology 2022 [88]	Theme 6	Printing small and individual building components	**Advantages:** 1. Manufacture uniquely shaped structures 2. Reduce manufacturing time 3. Effective control of pollution 4. Easily control the detailing and finish of the structure **Control:** Fully autonomous **Disadvantages:** 1. Longer manufacture times than the traditional method 2. Require skilled operators
Saidi et al. 2016 [12]	Theme 8, Category 8-1	Remotely controlled excavation	**Advantages:** 1. Reduced exposure of humans to hazards 2. Reduce labour needs **Control:** Teleoperated **Disadvantages:** 1. Remote control increases the cognitive load 2. Additional training of operators 3. Capital outlay for equipment
HK Tuen Mun 2022 [89]	Theme 8, Category 8-1	Increased boring speed and tunnel construction	**Advantages:** 1. Large working area 2. Higher tunnel boring speed than traditional tunnelling 3. Reduction in number of workers **Control:** Teleoperated **Disadvantages:** 1. Require skilled operators 2. Hard to transport to construction location
Bock and Linner 2016 [25]	Theme 5, Category 5-2	Heavy bar positioning	**Advantages:** 1. High accuracy installation 2. Reduced manual lifting therefore reduced occupational health hazard **Control:** Semi-autonomous **Disadvantages:** Require highly skilled operators
Bock and Linner 2016 [25]	Theme 5, Category 5-1	Roof cover installation	**Advantages:** 1. Increased speed of the roof installation 2. High-accuracy roof panel installation 3. Reduction in human labour requirements 4. Reduced manual lifting therefore reduced occupational health hazard **Control:** Fully autonomous **Disadvantages:** The size of installed roof is limited by robot size

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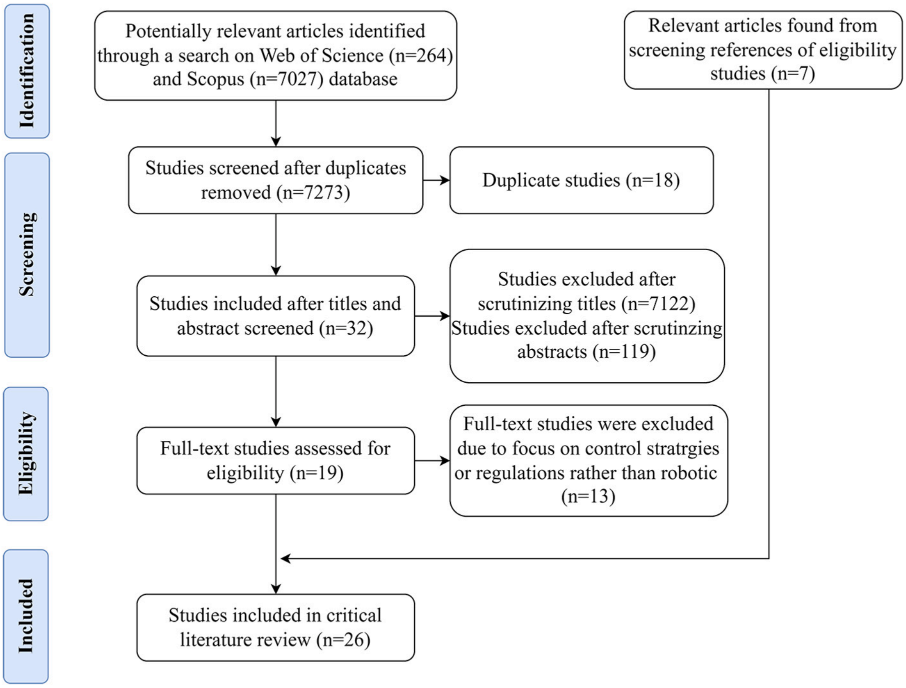

Fig. 2. Flowchart of literature search and selection.

Table 1 (*continued*)

Source&Year [Ref]	Classification	Objective	Features
Cybe 2022 [90]	Theme 1	Printing the whole house contour—regular structure	**Advantages:** 1. Increased construction speeds 2. Enables construction of more complex geometries 3. Easy to transport **Control:** Fully autonomous **Disadvantages:** 1. Require skilled operators 2. High capital investment
Brown 2012 [91]	Theme 1, Category 1-3	Transport and excavation	**Advantages:** 1. Reduce production cost 2. Reduce the duration of task performing 3. Compatible with current equipments **Control:** Teleoperated **Disadvantages:** Long-distance transmission has high latency
Ekso 2021 [92]	Theme 1, Category 1-7	Human augmentation	**Advantages:** 1. Reduce human physical exertion 2. Low weight 3. Reduce manual handling injuries 4. Easy and comfortable to don on and off **Control:** Teleoperated **Disadvantages:** Limited weight support

3.2. Potential ability robotic technology of reducing airborne viruses transmission and barriers to implementation

In total, 32 experts from the UK (n = 14, 44%) and China (n = 18, 56%) participated in the online questionnaire. Table 2 presents the characteristics of the experts who responded. More than half of the experts (n = 19, 59%) had more than 10 years of working experience in this field, while 69% (n = 22) had never used construction robotics before. Despite the limited experience in using construction robotics, most experts (n = 24, 75%) showed a positive attitude toward the use of construction robotics. Although most experts showed a positive attitude to using construction robotics, there were still some who were not keen on the use of robotics (UK = 2, China = 6). The main reasons were personal willingness, the requirement for operator training and the time required to set up the robotic systems.

Almost three-quarters (n = 23, 72%) of the experts who responded work in construction and one quarter (n = 8, 25%) work in university or academic settings. The majority of the experts were from construction engineering (n = 11, 34%) followed by geotechnical engineering (n = 10, 31%) disciplines. Although we received some experts' responses from countries other than the UK and China, we did not include them in our analysis as this was beyond the scope of our research.

3.2.1. Perceived benefits and implementation barriers of construction robotics

The perceived benefits and implementation barriers of using construction robotics in the UK and China were identified through the online questionnaire with experts (Table 3). Increasing productivity and quality, promoting workers' health and safety and reducing the required workforce are the main advantages of using construction robotics. Although the benefits of using construction robotics have been widely known by experts, the adoption of construction robotics is low in both the UK and China due to the implementation barriers including high cost, extra training for robotics operation, and less awareness of new technology. The interview participants also stated that the application of construction robotics is low due to multiple implementation barriers which also aligns with the

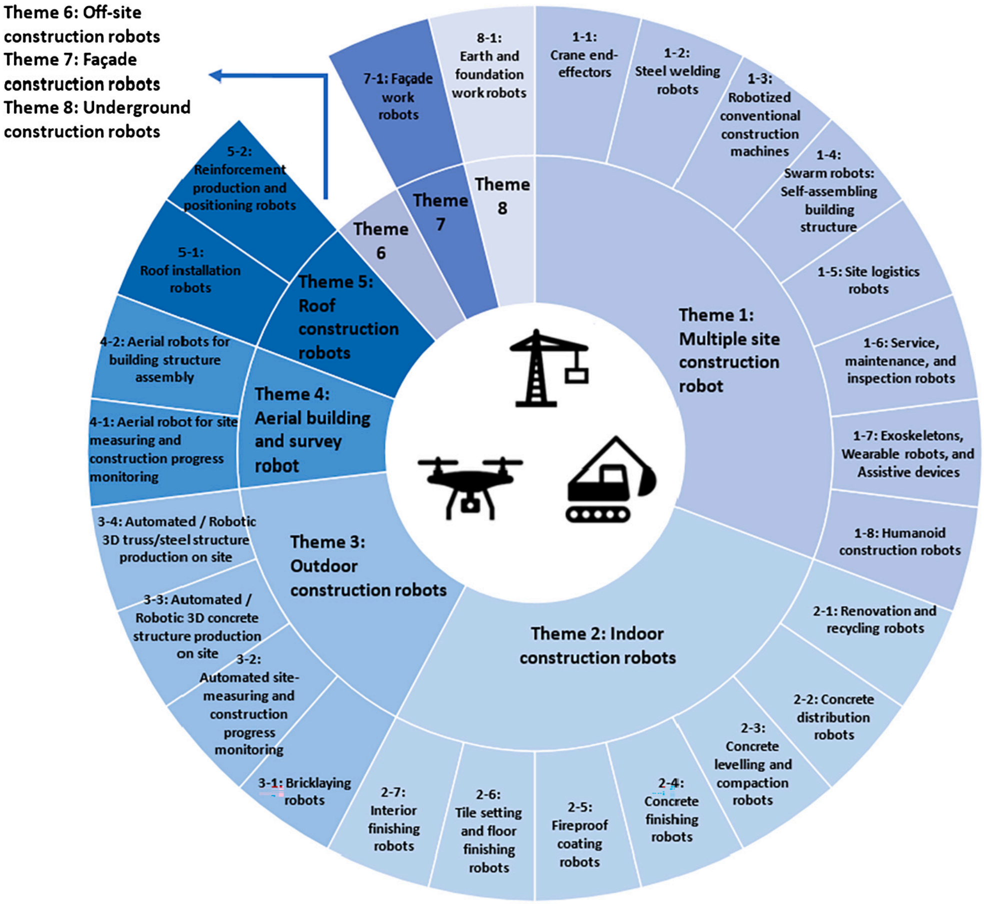

Fig. 3. Classification of Construction robotic technologies encompassing 8 themes (inner ring) and 25 categories (outer ring).

Table 2
Characteristics of participating experts in the UK and China through the online survey.

Characteristics	Number (%) of experts		
	UK	China	Total
Experts	14 (44%)	18 (56%)	32 (100%)
Profession and major*			
Construction Engineering	7 (22%)	4 (13%)	11 (34%)
Environmental Engineering	0 (0%)	4 (13%)	4 (13%)
Geotechnical Engineering	1 (3%)	9 (28%)	10 (31%)
Structural Engineering	2 (6%)	2 (6%)	4(13%)
Transportation Engineering	1 (3%)	0 (0%)	1 (3%)
Other	3 (9%)	3 (9%)	6 (19%)
Work organization*			
Construction industry	11 (34%)	12 (38%)	23 (72%)
Academia	5 (16%)	3 (9%)	8 (25%)
Other	1 (3%)	3 (9%)	4 (13%)
Working experience			
5—10 years' experience	5 (16%)	8 (25%)	13 (41%)
> 10 years' experience	9 (28%)	10 (31%)	19 (59%)
Experience of using construction robots			
Had experience	5 (16%)	5 (16%)	10 (31%)
Did not have experience	9 (28%)	13 (41%)	22 (69%)
Willingness to use construction robot			
Yes	12 (38%)	12 (38%)	24 (75%)
No	2 (6%)	6 (19%)	8 (25%)

* These are multiple selection questions, so totals exceed 100%

Table 3
General perceived benefits and implementation barriers of Construction robots in the UK and China from the questionnaire with 32 experts.

Perceived Benefits	Perceived implementation barriers
Improved health and safety	High cost
Improved product quality	Extra training for robotics operation
Reduced workforce requirements	High skilled/qualified operator required
Helping to complete difficult tasks	Complex operations of robotics
Increased working efficiency	Difficult to find suitable robotics
(e.g. reducing production time, increasing productivity)	Difficult to contact suppliers or request demos
	Size of the robotic is not suitable for institution

questionnaire and previous literature review results [3,20]. Particularly, the limited financial support from the government and high initial capital investment for technology is the main barrier to using more technology in industries. Moreover, the benefits and implementation barriers of construction robotics that consistent with the previous studies [3,20].

3.2.2. Robotics potential ability to reduce airborne virus transmission

The ranking results of 24 construction robotic systems according to the potential to reduce the transmission of airborne viruses are illustrated in Table 4. Regarding the four potentials: (1) the potential to increase the social distance between workers undertaking the same activity conventionally; (2) the potential to reduce the number of workers required to undertake the activity; (3) the potential to conduct the same activity remotely; (4) the potential to reduce the time taken to complete the activity), all robotic systems were reported having a medium or above the potential level from all experts responses. According to the Analysis of variance (ANOVA), the difference in country had no significant impact on the potential ranking results of almost all robotic systems ($P>0.05$).

All construction robotics showed a high total potential value (TPV) to reduce airborne virus (TPV≥9). All of them had a high potential to decrease the activity time except the roof construction robotics. Façade construction robotics showed the highest TPV to reduce airborne virus transmission in the construction industry due to the high distance between workers, low required workers, low activity time and high potential to work remotely. Construction robotics cannot reduce the required number of workers. The social distance between workers was ranked as having the lowest potential (TPV = 9) to reduce airborne transmission in the construction industry, such as the Ekso EVO exoskeleton.

4. Discussion

The findings of this research indicate that construction robotics has the potential to keep the construction industry going during a contagious virus pandemic, e.g. COVID-19, in both the UK and China. This technology can decrease the number of workers required for a task, increase social distance, help to conduct work remotely and reduce the duration of activities. The great patentability of construction robotics was identified through the literature review, interview and questionnaire with experts, while the current implementation barriers were also highlighted by the experts. Therefore, we identified and highlighted potential strategies that have been successfully utilised in other sectors (e.g. manufacturing or agriculture sector) to address the low adoption of robotics in the construction sector.

4.1. Potential of construction robotics to maintain construction industry operation during airborne virus

In total, 8 themes with 25 categories of construction robotics were identified through the literature review. However, many categories of construction robotics were only under the research stage; 24 commercially available robotic systems were identified through an additional internet search. The literature review results indicate robotics in the construction industry is generally used to prevent workers from exposure to hazards, reduce the number of workers required for activity and increase task accuracy, although many robotic systems require highly skilled operators, which is highly consistent with the online questionnaire results. These advantages also indicated a high potential of robotics to keep the construction industry active during the airborne virus (TPV≥9). The construction robotics with more potential to reduce the workforce required on the original basis and increase social distance had higher TPV, such as façade construction robots (Fig. 4A-C). Although most robotic technologies have huge potential advantages in reducing the required number of people or increasing social distance, in some cases, such as surveying and concrete levelling (Fig. 4D-E), this may make little practical difference because people are already distance due to the nature of the activity. The exoskeleton robotics (Fig. 4F) was reported as having the least potential to reduce airborne virus transmission in the construction industry because it cannot reduce the required workforce and social distance between workers. In addition, robotics were considered as having the potential to maintain productivity and reduce personnel on-site during the pandemic and participants for the questionnaire and interviewees have all shown a positive attitude towards their use not only during the airborne virus, such as the COVID-19 pandemic but also after the pandemic. It also indicated that the use of construction robotics can not only keep the construction sector safe and help maintain productivity amidst airborne viruses, other infectious viruses, and hazardous work environments. However, despite this potential, there seems to be limited adoption of construction robotics to reduce the transmission of airborne viruses due to various reasons including economic challenges, technical availability, and long deployment times. This is also in line with the general challenges of robotic adoption in the construction industry [16].

Table 4
Ranking results of construction robotic systems according to the potential to reduce the transmission of airborne virus.

No.	Theme	Category	Potential to reduce the transmission of airborne virus				
			Increase social distance*	Reduce labour needs*	Conduct work remotely*	Reduce operation time*	TPV
1	Facade construction robot	Façade work robot (glass cleaning)	High (3)	High (3)	High (3)	High (3)	12
2	Facade construction robot	Façade work robot (remote control)	High (3)	High (3)	High (3)	High (3)	12
3	Facade construction robot	Façade work robot (for cleaning and painting)	High (3)	High (3)	High (3)	High (3)	12
4	Off-site construction robots	Off-site construction robots (Assemble line)	High (3)	High (3)	High (3)	High (3)	12
5	Off-site construction robots	3D printing the whole irregular structure	High (3)	High (3)	High (3)	High (3)	12
6	Aerial building and survey robot	Site-measuring and construction progress monitoring	Medium (2.5)	High (3)	High (3)	High (3)	11.5
7	Outdoor ground construction robots	Bricklaying robots	High (3)	High (3)	Medium (2)	High (3)	11
8	Outdoor ground construction robots	Site-measuring and construction progress monitoring	High (3)	High (3)	Medium (2)	High (3)	11
9	Indoor construction robots	Concrete distribution robot	High (3)	High (3)	Medium (2)	High (3)	11
10	Indoor construction robots	Steel welding robot	High (3)	High (3)	Medium (2)	High (3)	11
11	Off-site construction robots	3D printing small building components	Medium (2)	High (3)	High (3)	High (3)	11
12	Underground construction robots	Earth and foundation work robots (excavation)	Medium (2.5)	High (3)	Medium (2)	High (3)	10.5
13	Underground construction robots	Earth and Foundation Work Robots (tunnel boring)	Medium (2)	Medium (2.5)	High (3)	High (3)	10.5
14	Indoor construction robots	Concrete Finishing Robots	Medium (2)	High (3)	Medium (2.5)	High (3)	10.5
15	Outdoor ground construction robots	3D Concrete Structure Production	High (3)	Medium (2)	Medium (2)	High (3)	10
16	Roof construction robots	Reinforcement production and positioning robots	Medium (2)	High (3)	Medium (2)	High (3)	10
17	Indoor construction robots	Tile setting and floor finishing robots	Medium (2)	High (3)	Medium (2)	High (3)	10
18	Indoor construction robots	Site logistics robots	Medium (2)	High (3)	Medium (2)	High (3)	10
19	Multiple site construction robots	Across multiple categories** (3D printing the whole house)	Medium (2.5)	Medium (2)	Medium (2)	High (3)	10
20	Facade construction robots	Façade work robot (for class installation)	Medium (2)	Medium (2.5)	Medium (2)	High (3)	9.5
21	Multiple site construction robots	Robotized conventional construction machines	Medium (2.5)	Medium (2)	Medium (2)	High (3)	9.5
22	Roof construction robot	Across multiple categories**	High (3)	Medium (2)	Medium (2)	Medium (2)	9
23	Indoor construction robots	Concrete levelling and compaction robots	Medium (2)	Medium (2)	Medium (2)	High (3)	9
24	Multiple site construction robots	Exoskeletons, Wearable robots, and Assistive devices	Medium (2)	Medium (2)	Medium (2)	High (3)	9

* Median value of all experts
** the construction robotics can be classified into different categories

In the next section, we highlight the strategies which have been successfully utilised by other areas of the UK and Chinese economies to stimulate the adoption of robotics to highlight strategies which may benefit their construction industries. Furthermore, we make additional evidence-based suggestions which may promote the adoption of technology.

4.2. Implementation barriers and strategies to promote adoption of construction robotics

The questionnaire and interview results indicate that most experts had a willingness to adopt the technology generally and with consideration given to the airborne virus (e.g. COVID-19) pandemic. We did not identify any significant differences in implementation barriers to the adoption of construction robotics between the UK and China ($P>0.05$), which aligns with the previous studies of the constriction robotic implementation in the UK [16] and China [34]. Although experts from both the UK and China have positive attitudes to adopting construction robotics, the main implementation barriers (e.g. high device cost, workforce skills gap, limited awareness of new technology and unclear economic benefit) still limit the adoption rate of construction robotics in the UK and China. Construction robotics have been reported as one of the most important technologies that can help increase productivity [46], yet the adoption rate in both the UK and China is low, both are less than 1% [21,46]. Conversely, robot adoption is high across other industries in both countries. According to Cheng et al., robotics adoption in the manufacturing industry in China was around 44.5% in 2019 [95]. Also in the UK, the robotic per million hours worked in the warehouse logistics sector was 3.3 in 2020, which was around 33 times higher than in the construction sector [21]. Although many studies have identified the implementation barriers of construction robotics [3,20,34], they do not provide suitable strategies to address these barriers. However, increasing

Fig. 4. Examples of commercialised construction robotics. A: Robosoft—Facade work robot for roof glass cleaning [84]; B: INVERT ROBOTICS—Façade work robot for remotely controlled robotic crawler with vision modules [85]; C: SB Multi-Coater robot—Façade work robot for wall painting [86]; D: LiDAR USA Snoopy A-Series 120—Aerial robots for site-measuring and construction progress monitoring [93]; E: LOM 110—Concrete levelling and compaction robots [72]; F: EksoEVO exoskeleton— Multiple site construction robots [94] (All images are reused with permission from respective sources).

the level of adoption requires implementation barriers which have been known for over 40 years to be addressed. In the preceding paragraphs, we review the four major barriers preventing greater adoption of robotics within the construction industry. The identified implementation barriers to construction robotics have also been general barriers to the adoption of new technologies in other sectors, including manufacturing [96,97], agriculture [98,99], and oil and gas sectors [100–103]. However, these sectors have addressed the adoption barriers. Thus we are proposing that the strategies adopted by these sectors could be utilised as a model for construction robotics adoption.

4.2.1. High initial capital costs

Economic considerations including high capital cost and limited financial support from the government have been highlighted as major barriers to the adoption of technology in the construction industry [17]. Even without the airborne virus pandemic, the adoption of robots in the construction sector is slower than in other industries due to the high implementation cost and low commercial availability [87]. For example, the robotic density (the number of robotics per 1000 employees) in the construction sector was 1.2 in the European Union (EU), while it was 160 in the manufacturing sector in 2017 [104]. This barrier has existed since the early development stages of construction robotics and has persisted for more than 40 years [30,31,33]. Research suggests that it is the higher-cost robotic technology which faces a barrier to adoption [105,106], and lower-cost robotics are more acceptable to the construction industry [16,46]. For example, exoskeleton robotics, especially passive exoskeleton robots have been widely adopted in the construction sector due to their relatively low cost and potential to increase productivity and reduce injury [107–109]. The higher cost robotic systems also have been adopted, such as Concrete Masonry Units (CMUs) robots or bricklaying robots, but not to the same extent as exoskeletons [71]. Although the UK and Chinese governments have provided financial support for their construction industries, especially during the COVID-19 pandemic [110,111], it may still be difficult for small or middle-scale companies to get sufficient economic support to drive adoption. Compared to large construction companies, smaller construction companies usually have a smaller budget for technology and therefore would require more financial support from governments to address high capital cost barriers [21]. Furthermore, the practice of large corporations subcontracting smaller firms to carry out work results in small and medium-sized enterprises (SMEs) bearing the cost burden, rather than the larger companies.

Publishing policies to support technology adoption would be a solution and has already been demonstrated in other sectors, such as manufacturing and agriculture sectors in Europe and China. The European Union, EU Horizon 2020 project [112] has provided 79 billion euros of support for new technology innovation in 2020 with some success [113,114]. This program provides a range of different funding schemes, including collaborative projects involving multiple partners from different countries, individual fellowships for researchers, and SMEs looking to develop innovative products and services [113,114]. Through this initiative, a series of new technologies has been developed and adopted in different sectors that improved productivity and economics. For example, a new robot, SWEEPER, has been adopted for greenhouse harvesting which has increased the harvest performance from 29% to 61% [113]. Apart from the agriculture sector, the vehicle manufacturing sector also benefits from EU Horizon. For instance, by using RECOTRANS, a new manufacturing system, the production time was reduced up to 50% and the cost up to 35% from 2017 to 2021 [115]. In terms of China, the government has continued its strategy of setting Five-Year Plans, something it has done since 1953, to provide financial support to encourage technology adoption [116]. However, in the previous Five-Year Plans, the priority areas for the development of industries were manufacturing, new materials, biotechnology and agriculture rather than the construction industry [117,118], which was one of the potential reasons for the slower robotics adoption in the construction sector. Through its 13th Five-Year Plan (2016—2020), the comprehensive mechanization rate of agriculture reached 71% in 2020, an increase of 6 percentage points over 2016 [119]. Thus, we propose that publishing suitable policies to provide financial support can increase construction robotics adoption as well as productivity.

Providing tax credits or reducing the tax could be another solution for the high cost. The tax treatment of capital expenditures in the UK, where the corporate tax rate is 19% [120], is less generous than in Singapore, which has a 17% corporate tax rate [121]. This may dampen the robotics investments and adoption. Additionally, manufacturing companies in South Korea receive tax credits for investment in new equipment, which helped South Korea become the largest adopter of robotics in the industry in 2017, with 710 robots per 10,000 workers [46].

In addition to providing funding for technology innovation, increasing the Public-Private Partnership (PPP) between industry and government is also utilised for motivating technology adoption in many sectors. According to the definition, "PPP programme provides a long-term, sustainable approach to improve social infrastructure, enhancing the value of public assets and making better use of taxpayer's money" [122]. In terms of the construction sector in the UK and China, the government is the biggest client of the construction industry, and can therefore help increase the adoption by promoting the cooperation between academia and research institutes, and economic incentives [123]. A good example is the Factories of the Future contractual Public-Private Partnership (FoF PPP) launched by the European Commission to increase the new technologies and system development across multiple sectors in the European Union's [124,125], which received 983 technology innovations for the advanced manufacturing process, digitalisation, human-machine interaction and other areas with 94 awarded patents in 2017 [126]. Therefore, providing funding for technology innovation and increasing the collaboration between the construction industry and governments would be a good solution to reduce the high initial capital cost in both the UK and China.

4.2.2. Workforce skills gap

Skill shortage is a common barrier to the rapid adoption of new technology [127], especially for SMEs [128]. The construction industry workforce does not have the necessary skills to adopt some technologies [129]. Training the workforce to achieve the necessary qualifications and experience to operate more complex robotic systems requires extra time and costs, which is a barrier to implementation. According to the interviews in this research we have conducted with industry experts, robots that require less training or experienced operators may gain higher acceptance and adoption, which aligns with Pan's research in 2020 into the influencing factors for the development of construction robot technology [130].

Dorota et al. pointed out the lack of technology awareness caused the skill shortage in 2017 [131], and more advanced technology adoption caused a larger skill gap and shortage [132]. Providing training, such as computer literacy training and technical skills training for workers is the common way to address the workforce skills gap due to its low cost [133]. Boothby et al. in 2010 [127] identified providing training can also transfer stakeholders' attitudes to adopting new technology and increase the productivity effect by more than 50%. However, there is insufficient funding when the industry tries to provide enough training for all employees [134]. Hence, as suggested by Boothby et al. [127] the government should establish co-ordinate policies to support the technology training delivery, and a good example is the "Digital Skills Partnership" (DSP) initiative in the UK. DSP is a program providing collaboration between governments, industries, and training providers to address the digital skills (e.g. coding, web design and digital marketing) gap and increase the number of workers trained in digital technologies [135]. From an industry's perspective, they obtain more trained workers at less cost. A good example is the Heart of The South West Bounce Back Digital programme, which provides online digital skill tutorials to more than 800 businesses [136]. Hence, a mix of industries and governments' actions are needed to address the workforce skills gap during new technology adoption.

4.2.3. Limited awareness of new technologies

Our questionnaire with experts found that the limited awareness of the new technologies directly leads to low construction robotics adoption, which includes but is not limited to difficulty in getting information on new technology (e.g. cost and installation time of robotics, the development and trend of current construction robotics), difficulty in finding and deciding suitable robotics for industries (e.g. suitable robotic size for the industry). Although previous research highlighted the lack of awareness of the new technology, assessment and selection are still barriers preventing increased construction robotics adoption [137], which has not been addressed. Therefore, the government initiative and construction suppliers' support may be required to promote the construction robotics adoption.

The main strategy for increasing stakeholders' awareness of technology is to increase the technical knowledge in the construction sector. Unlike academia, stakeholders in the industry have fewer opportunities to participate in seminars and conferences to up-know the current trend of technology in industry [138]. Attending events (e.g. seminars and conferences) to build a strong professional network is a good way for industry stakeholders to increase their awareness of the latest technology as well as the risk perception [138], which could also be utilised in the construction sector. An example of such events was the 14 events held throughout Europe in 2017 by the Fof PPP to support the network between industry and researchers [124,125]. Furthermore, strengthening the link between industry and educational institutions is also regarded as an efficient way to increase stakeholders' awareness and investment by providing more applications and technologies that can be directly applicable and advantageous to the industry. In 1999, Premkumar and Roberts highlighted the positive impact of education and training on increasing stakeholders' awareness of new technology [139], which indicates the strategies used to address the skill gap can also be used to increase the technology awareness of stakeholders. A good example is the University Cooperative Research Centers (IUCRCs) Program The National Science Foundation (NSF) Industry runs. This program aims to develop new technologies through collaborative research between industry and academia [140]. According to the IUCRC report, most industry members (90%-95%) obtained technical advice or training, which may have a positive effect on further new technology adoption [141].

In China, the government established 'Made in China 2025' in 2015 and aimed to motivate technological innovation and adoption to achieve smart manufacturing [142]. As a result, the robot density increased to 461 per 10,000 employees in the Shanghai Electric industry, the productivity doubled in Haier Company and the productivity increased by 24% in Sany Company [142].

Apart from the governments, the robotic supplier or the construction robotics industry association can also provide support for increasing stakeholders' awareness. For example, Universal Robots, KUKA and Yaskawa, provide free online training course that allows users to program, operate and maintain their robots [143]. Industries may have more willingness to adopt robotics if the suppliers provide suitable training. In terms of the association, most current events from UK and China construction industry associations focus on providing information related to career, skill training, and industry development rather than introducing new technologies, such as Build UK [144] and China Association of Construction Enterprises [145]. We propose that if these big associations could introduce more new technologies, the stakeholders' awareness would be increased.

4.2.4. Unclear economic benefit

Unlike sectors such as manufacturing which evidence demonstrates increased manufacturing output with the adoption of robotics [146], the benefit to construction is less clear [4,147]. Although in 2018 Pan et al. [148] indicated the economic benefit of construction automation and robotics, they only focused on the sustainability of robotics rather than the economic benefit of adopting construction robotics. Davila Delgado et al. [16] in 2019 stated the economic benefits are not clear which aligns with our questionnaire results. The result is that unclear economic benefits pose a barrier for the industry to adopt and realise the benefit of construction robotics.

Although the potential economic benefits of robotics adoption are not straightforward [21], we could determine that they are directly reflected in productivity and robotic adoption rate [149–151]. According to the UK Department for Business, Energy & Industrial Strategy's report Robotics and autonomous systems: the economic impact across UK sectors, 2021, by increasing productivity, the estimated cost can be saved up to 10% for the off-site prefabrication tasks [152]. In addition, this report highlights that if the potential construction robotic adoption rate is achieved (38%), the Gross Value Add (GVA) could reach £10.6 billion by 2035, more than 100 times higher than in 2018 [152]. A recent study conducted by Hu et al. investigated the potential economic benefit of construction robotics by a case study of a cable-driven façade installation robot [153]. However, this economic benefit was obtained from a prototype rather than a commercialised construction robot. Long-term investigation is required to get the clear economic benefit of using construction robotics. Despite the unclear economic benefit of robotics, adoption in the construction sector can be addressed readily by government policies. Policymakers in the UK and China could help either by funding the robotic and automation system, increasing technology innovation, or providing skill training to motivate robotic adoption.

Although the UK and China governments published some policies to support the technology adoption in the construction sector, such as UK's 'Construction 2025' project (2013-2025) [123] and 14th Five-Year Plan (2021-2025) [154], there still is a long way to achieve high adoption rate.

5. Conclusion

This work investigated the latest commercialised construction robotics and the future potential of construction robotics used as a technology shield to reduce or prevent the transmission of airborne viruses in the construction industry. One contribution of this study is that we identified that construction robots are not only beneficial to reduce airborne virus transmission, but also help to keep the construction industry operating safely. Secondly, this work identified and discussed experts' views on using construction robotics in the UK and China. Most experts showed a positive attitude to using construction robotics but the adoption rate in both the UK and China is low (<1%). This work also identified implementation barriers of construction robotics are the same in both the UK and China. Thirdly, this work proposes potential strategies to overcome implementation barriers of construction robotics which have been known since the 1980s and have not yet been diminished. One contribution of this study is that identified the potential strategies to overcome the implementation barriers, which are: 1) the high initial cost of robotics could be addressed through government funding and taxation strategy; 2) the workforce skills gap could be solved by training provided by government or industry; 3) the limited awareness of new technologies barrier could be overcome through coordinated seminars and conferences to develop familiarity with new technologies; 4) the economic advantages of incorporating construction robotics would be more discernible with a higher adoption rate of robotics in the construction industry. Growing robotics within the construction sector could be achieved through the strategies mentioned above, which have been developed by learning from successful solutions adopted in other sectors, such as manufacturing and agriculture, for the adoption of new technologies. In addition to the attitude of the construction industry itself, the British and Chinese governments, as the largest customers, also could provide sufficient support. Additionally, the UK and China were selected as example of developed and developing countries respectively, thus, the results of this study can also be the guidance for other countries having a low construction robotics adoption rate.

Limitation There are some limitations of this study. First, the number of questionnaire participants from industry was greater than that from academia. The results of this study may vary with the number of experts from university or academic areas. For further research, more experts from academics should be involved. Second, although the interview participants were from the top 10 construction sectors in the UK, the sample size was small (n = 4) and they were based in the UK. More interviews with construction companies in both of UK and China are required for further research.

Ethics statement

According to the regulation for ethical approval in the Faculty of Science and Engineering at the University of Manchester (UoM) and the results of the UoM ethics assessment, ethical approval was not required to undertake this questionnaire and online interview; all responses were anonymised and not include any sensitive or personal data. Before conducting the questionnaire, a participant information sheet (PIS) and a consent form were provided to participants (Appendix 1).

CRediT authorship contribution statement

Lutong Li: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation. **Pu Yuan:** Writing – review & editing, Writing – original draft, Methodology, Data curation. **Yuan Tang:** Writing – review & editing, Visualization. **Glen Cooper:** Writing – original draft, Project administration, Funding acquisition, Conceptualization. **Simon Thurlbeck:** Writing – review & editing, Project administration, Funding acquisition. **Clara Man Cheung:** Writing – review & editing, Project administration, Methodology, Funding acquisition, Data curation, Conceptualization. **Patrick Manu:** Writing – review & editing, Project administration, Methodology, Funding acquisition. **Akilu Yunusa-Kaltungo:** Writing – review & editing, Project administration, Funding acquisition. **Andrew Weightman:** Writing – review & editing, Resources, Project administration, Investigation, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability statement

The data that support the findings of this study are not publicly available due to privacy concerns and ethical considerations. However, the data may be made available upon reasonable request. Researchers interested in accessing the data are invited to contact the author to discuss the possibility of obtaining the necessary permissions and access.

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Appendix A. Supplementary material

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e29697.

References

[1] M. Taraz, M. Ghasempourabadi, Human-robot interaction in construction: a literature review, Malays. J. Sustain. Environ. 8 (1) (2021) 49–74, https://doi.org/10.24191/myse.v8i2.13236.
[2] T. Bock, Construction robotics, Auton. Robots 22 (3) (2007) 201–209, https://doi.org/10.1007/s10514-006-9008-5.
[3] M. Gharbia, A. Chang-Richards, Y. Lu, R.Y. Zhong, H. Li, Robotic technologies for on-site building construction: a systematic review, J. Build. Eng. 32 (2020) 101584, https://doi.org/10.1016/j.jobe.2020.101584.
[4] T. Bock, The future of construction automation: technological disruption and the upcoming ubiquity of robotics, Autom. Constr. 59 (2015) 113–121, https://doi.org/10.1016/j.autcon.2015.07.022.
[5] S.H. Ghaffar, J. Corker, M. Fan, Additive manufacturing technology and its implementation in construction as an eco-innovative solution, Autom. Constr. 93 (2018) 1–11, https://doi.org/10.1016/j.autcon.2018.05.005.
[6] B. Panda, S.C. Paul, L.J. Hui, Y.W.D. Tay, M.J. Tan, Additive manufacturing of geopolymer for sustainable built environment, J. Clean. Prod. 167 (2017) 281–288, https://doi.org/10.1016/j.jclepro.2017.08.165.
[7] E. Lublasser, T. Adams, A. Vollpracht, S. Brell-Cokcan, Robotic application of foam concrete onto bare wall elements - analysis, concept and robotic experiments, Autom. Constr. 89 (2018) 299–306, https://doi.org/10.1016/j.autcon.2018.02.005.
[8] C. Feng, Y. Xiao, A. Willette, W. McGee, V.R. Kamat, Vision guided autonomous robotic assembly and as-built scanning on unstructured construction sites, Autom. Constr. 59 (2015) 128–138, https://doi.org/10.1016/j.autcon.2015.06.002.
[9] T. Linner, W. Pan, R. Hu, C. Zhao, K. Iturralde, M. Taghavi, J. Trummer, M. Schlandt, T. Bock, A technology management system for the development of single-task construction robots, Constr. Innov. 20 (1) (2020) 96–111, https://doi.org/10.1108/CI-06-2019-0053.
[10] S. Kim, M. Peavy, P.-C. Huang, K. Kim, Development of bim-integrated construction robot task planning and simulation system, Autom. Constr. 127 (2021) 103720, https://doi.org/10.1016/j.autcon.2021.103720.
[11] K. Iturralde, M. Feucht, D. Illner, R. Hu, W. Pan, T. Linner, T. Bock, I. Eskudero, M. Rodriguez, J. Gorrotxategi, et al., Cable-driven parallel robot for curtain wall module installation, Autom. Constr. 138 (2022) 104235, https://doi.org/10.1016/j.autcon.2022.104235.
[12] K.S. Saidi, T. Bock, C. Georgoulas, Robotics in Construction, Springer International Publishing, Cham, 2016, pp. 1493–1520.

[13] T.H. Davenport, J. Kirby, Beyond automation, Harv. Bus. Rev. 93 (6) (2015) 58–65.
[14] M.J. Kim, H.-L. Chi, X. Wang, L. Ding, Automation and robotics in construction and civil engineering, J. Intell. Robot. Syst. 79 (3) (2015) 347–350, https://doi.org/10.1007/978-3-030-51295-8_72.
[15] S. Cai, Z. Ma, X. Xiang, Trends of research and development on construction robotics considering the supporting technologies and successful applications, in: Proceedings of the 18th International Conference on Computing in Civil and Building Engineering: ICCCBE 2020, Springer, 2021, pp. 1037–1051.
[16] J.M. Davila Delgado, L. Oyedele, A. Ajayi, L. Akanbi, O. Akinade, M. Bilal, H. Owolabi, Robotics and automated systems in construction: understanding industry-specific challenges for adoption, J. Build. Eng. 26 (2019) 100868, https://doi.org/10.1016/j.jobe.2019.100868.
[17] F. Bademosi, R.R.A. Issa, Factors influencing adoption and integration of construction robotics and automation technology in the US, J. Constr. Eng. Manage. 147 (8) (2021) 04021075, https://doi.org/10.1061/(ASCE)CO.1943-7862.0002103.
[18] R. Agarwal, S. Chandrasekaran, M. Sridhar, Imagining construction's digital future, McKinsey & Company, 2016.
[19] N. Kumar, N. Hack, K. Doerfler, A.N. Walzer, G.J. Rey, F. Gramazio, M.D. Kohler, J. Buchli, Design, development and experimental assessment of a robotic end-effector for non-standard concrete applications, in: 2017 IEEE International Conference on Robotics and Automation (ICRA), 2017, pp. 1707–1713.
[20] S. Cai, Z. Ma, M.J. Skibniewski, S. Bao, Construction automation and robotics for high-rise buildings over the past decades: a comprehensive review, Adv. Eng. Inform. 42 (2019) 100989, https://doi.org/10.1016/j.aei.2019.100989.
[21] D. Herr, M. Godel, R. Perkins, L. Pate, T. Hall, The economic impact of robotics & autonomous systems across UK sectors, 2020.
[22] E. Gambao, C. Balaguer, F. Gebhart, Robot assembly system for computer-integrated construction, Autom. Constr. 9 (5) (2000) 479–487, https://doi.org/10.1016/S0926-5805(00)00059-5.
[23] Y. Terada, S. Murata, Automatic modular assembly system and its distributed control, Int. J. Robot. Res. 27 (3–4) (2008) 445–462, https://doi.org/10.1177/0278364907085562.
[24] S.A. Howe, B.H. Wilcox, C. McQuin, J. Townsend, R.R. Rieber, M. Barmatz, J. Leichty, Faxing structures to the moon: freeform additive construction system (facs), in: AIAA SPACE 2013 Conference and Exposition, 2013, p. 5437.
[25] T. Bock, T. Linner, Integrated Automated/Robotic on-Site Factories, Cambridge University Press, 2016, pp. 1–7.
[26] https://www.mckinsey.com/mgi/overview/in-the-news/the-construction-industry-has-a-productivity-problem. (Accessed 6 March 2022).
[27] M. Loosemore, Improving construction productivity: a subcontractor's perspective, Eng. Constr. Archit. Manag. 21 (3) (2014) 245–260, https://doi.org/10.1108/ECAM-05-2013-0043.
[28] T. Linner, Automated and robotic construction: integrated automated construction sites, Thesis, 2013.
[29] G. Carra, A. Argiolas, A. Bellissima, M. Niccolini, M. Ragaglia, Robotics in the construction industry: state of the art and future opportunities, in: ISARC, in: Proceedings of the International Symposium on Automation and Robotics in Construction, vol. 35, IAARC Publications, 2018, pp. 1–8.
[30] A. Warszawski, R. Navon, Implementation of robotics in building: current status and future prospects, J. Constr. Eng. Manage. 124 (1) (1998) 31–41, https://doi.org/10.1061/(ASCE)0733-9364(1998)124:1(3.
[31] J.S. Russell, M.J. Skibniewski, An ergonomic analysis framework for construction tasks, Constr. Manag. Econ. 8 (3) (1990) 329–338, https://doi.org/10.1080/01446199000000027.
[32] M.J. Skibniewski, Framework for decision 2010; making on implementing robotics in construction, J. Comput. Civ. Eng. 2 (2) (1988) 188–201, https://doi.org/10.1061/(ASCE)0887-3801(1988)2:2(188).
[33] M. Skibniewski, C. Hendrickson, Analysis of robotic surface finishing work on construction site, J. Constr. Eng. Manage. 114 (1) (1988) 53–68, https://doi.org/10.1061/(ASCE)0733-9364(1988)114:1(53).
[34] X. Chen, A.Y. Chang-Richards, A. Pelosi, Y. Jia, X. Shen, M.K. Siddiqui, N. Yang, Implementation of technologies in the construction industry: a systematic review, Eng. Constr. Archit. Manag. (2021), https://doi.org/10.1108/ECAM-02-2021-0172.
[35] B. Hu, H. Guo, P. Zhou, Z.-L. Shi, Characteristics of sars-cov-2 and covid-19, Nat. Rev. Microbiol. 19 (3) (2021) 141–154, https://doi.org/10.1038/s41579-020-00459-7.
[36] L. Piroth, J. Cottenet, A.-S. Mariet, P. Bonniaud, M. Blot, P. Tubert-Bitter, C. Quantin, Comparison of the characteristics, morbidity, and mortality of covid-19 and seasonal influenza: a nationwide, population-based retrospective cohort study, Lancet Respir. Med. 9 (3) (2021) 251–259, https://doi.org/10.1016/S2213-2600(20)30527-0.
[37] E. Petersen, M. Koopmans, U. Go, D.H. Hamer, N. Petrosillo, F. Castelli, M. Storgaard, S. Al Khalili, L. Simonsen, Comparing sars-cov-2 with sars-cov and influenza pandemics, Lancet Infect. Dis. 20 (9) (2020) e238–e244, https://doi.org/10.1016/S1473-3099(20)30484-9.
[38] Y. Yang, A.P.C. Chan, M. Shan, R. Gao, F. Bao, S. Lyu, Q. Zhang, J. Guan, Opportunities and challenges for construction health and safety technologies under the covid-19 pandemic in Chinese construction projects, Int. J. Environ. Res. Public Health 18 (24) (2021) 13038, https://doi.org/10.3390/ijerph182413038.
[39] F. Pottier, Review of early estimates of construction output for gdp, 2008.
[40] https://www.constructionnews.co.uk/financial/65-of-uks-construction-value-shut-down-31-03-2020/. (Accessed 22 April 2022).
[41] https://www.ons.gov.uk/businessindustryandtrade/constructionindustry/bulletins/constructionoutputingreatbritain/march2021. (Accessed 22 April 2022).
[42] https://www.chas.co.uk/blog/covid-impact-on-construction-industry/. (Accessed 22 April 2022).
[43] S. Suresh, S. Renukappa, M. Stride, The impact of covid-19 on the UK construction industry, 2020.
[44] A. Biswas, A. Ghosh, A. Kar, T. Mondal, B. Ghosh, D.P.K. Bardhan, The impact of covid-19 in the construction sector and its remedial measures, J. Phys. Conf. Ser. 1797 (1) (2021) 012054, https://doi.org/10.1088/1742-6596/1797/1/012054.
[45] K. Liu, Covid-19 and the Chinese economy: impacts, policy responses and implications, in: The Political Economy of Covid-19, Routledge, 2022, pp. 200–222.
[46] R.D. Atkinson, Which nations really lead in industrial robot adoption?, Information Technology & Innovation Foundation, 2018.
[47] B. Xiao, C. Chen, X. Yin, Recent advancements of robotics in construction, Autom. Constr. 144 (2022) 104591, https://doi.org/10.1016/j.autcon.2022.104591.
[48] S.O. Abioye, L.O. Oyedele, L. Akanbi, A. Ajayi, J.M. Davila Delgado, M. Bilal, O.O. Akinade, A. Ahmed, Artificial intelligence in the construction industry: a review of present status, opportunities and future challenges, J. Build. Eng. 44 (2021) 103299, https://doi.org/10.1016/j.jobe.2021.103299.
[49] N.K. Bourne, H. Balmforth, H. Beers, R. Cao, C. Cheung, S. Clarke, W. Collinge, G. Cooper, E. Corbett, A. Hartwig, Keeping the UK building safely: a scoping study: Prepared for: the protect covid-19 national core study on transmission and environment 2021.
[50] M.R. Hallowell, J.A. Gambatese, Qualitative research: application of the delphi method to cem research, J. Constr. Eng. Manage. 136 (1) (2010) 99–107, https://doi.org/10.1061/(ASCE)CO.1943-7862.0000137.
[51] A. Poghosyan, P. Manu, A.-M. Mahamadu, O. Akinade, L. Mahdjoubi, A. Gibb, M. Behm, A web-based design for occupational safety and health capability maturity indicator, Saf. Sci. 122 (2020) 104516, https://doi.org/10.1016/j.ssci.2019.104516.
[52] M. Asah-Kissiedu, P. Manu, C.A. Booth, A.-M. Mahamadu, K. Agyekum, An integrated safety, health and environmental management capability maturity model for construction organisations: a case study in Ghana, Buildings 11 (12) (2021) 645, https://doi.org/10.3390/buildings11120645.
[53] P. Manu, A. Poghosyan, A.-M. Mahamadu, L. Mahdjoubi, A. Gibb, M. Behm, O.O. Akinade, Design for occupational safety and health: key attributes for organisational capability, Eng. Constr. Archit. Manag. 26 (11) (2019) 2614–2636, https://doi.org/10.1108/ECAM-09-2018-0389.
[54] G. Guest, A. Bunce, L. Johnson, How many interviews are enough?: an experiment with data saturation and variability, Field Methods 18 (1) (2006) 59–82, https://doi.org/10.1177/1525822X05279903.
[55] W. Lin, H. Luo, Robotic Welding, Springer London, London, 2015, pp. 2403–2444.
[56] S. Gusmao Brissi, O. Wong Chong, L. Debs, J. Zhang, A review on the interactions of robotic systems and lean principles in offsite construction, Eng. Constr. Archit. Manag. 29 (1) (2022) 383–406, https://doi.org/10.1108/ECAM-10-2020-0809.

[57] E. Gambao, M. Hernando, Control system for a semi-automatic façade cleaning robot, in: Proceedings of the 2006 International Symposium of Automation and Robotics in Construction, 2006, pp. 406–411.
[58] S. De Bock, J. Ghillebert, R. Govaerts, B. Tassignon, C. Rodriguez-Guerrero, S. Crea, J. Veneman, J. Geeroms, R. Meeusen, K. De Pauw, Benchmarking occupational exoskeletons: an evidence mapping systematic review, Appl. Ergon. 98 (2022) 103582, https://doi.org/10.1016/j.apergo.2021.103582.
[59] 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 (3) (2017) 261–276, https://doi.org/10.1080/17452759.2017.1326724.
[60] P. Wu, J. Wang, X. Wang, A critical review of the use of 3-d printing in the construction industry, Autom. Constr. 68 (2016) 21–31, https://doi.org/10.1016/j.autcon.2016.04.005.
[61] 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. Constr. 89 (2018) 110–119, https://doi.org/10.1016/j.autcon.2017.12.031.
[62] B.-S. Chu, D.-N. Kim, D.-H. Hong, Robotic automation technologies in construction: a review, Int. J. Precis. Eng. Manuf. 9 (3) (2008) 85–91.
[63] Z. Xu, T. Song, S. Guo, J. Peng, L. Zeng, M. Zhu, Robotics technologies aided for 3d printing in construction: a review, Int. J. Adv. Manuf. Technol. 118 (11) (2022) 3559–3574, https://doi.org/10.1007/s00170-021-08067-2.
[64] S. Zhou, M. Gheisari, Unmanned aerial system applications in construction: a systematic review, Constr. Innov. 18 (4) (2018) 453–468, https://doi.org/10.1108/CI-02-2018-0010.
[65] P. Nooralishahi, C. Ibarra-Castanedo, S. Deane, F. López, S. Pant, M. Genest, N.P. Avdelidis, X.P.V. Maldague, Drone-based non-destructive inspection of industrial sites: a review and case studies, Drones 5 (4) (2021) 106, https://doi.org/10.3390/drones5040106.
[66] T. Rakha, A. Gorodetsky, Review of unmanned aerial system (uas) applications in the built environment: towards automated building inspection procedures using drones, Autom. Constr. 93 (2018) 252–264, https://doi.org/10.1016/j.autcon.2018.05.002.
[67] S. Chen, D.F. Laefer, E. Mangina, State of technology review of civilian uavs, Rec. Pat. Eng. 10 (3) (2016) 160–174, https://doi.org/10.2174/1872212110666160712230039.
[68] J. Khakurel, H. Melkas, J. Porras, Tapping into the wearable device revolution in the work environment: a systematic review, Inf. Technol. People 31 (3) (2018) 791–818, https://doi.org/10.1108/ITP-03-2017-0076.
[69] 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. Constr. 18 (3) (2009) 239–248, https://doi.org/10.1016/j.autcon.2008.09.002.
[70] Y. Ham, K.K. Han, J.J. Lin, M. Golparvar-Fard, Visual monitoring of civil infrastructure systems via camera-equipped unmanned aerial vehicles (uavs): a review of related works, Vis. Eng. 4 (1) (2016) 1, https://doi.org/10.1186/s40327-015-0029-z.
[71] N. Melenbrink, J. Werfel, A. Menges, On-site autonomous construction robots: towards unsupervised building, Autom. Constr. 119 (2020) 103312, https://doi.org/10.1016/j.autcon.2020.103312.
[72] T. Bock, T. Linner, Construction RobotsElementary Technologies and Single-Task Construction Robots, Cambridge University Press, 2016.
[73] C. Balaguer, M. Abderrahim, Trends in robotics and automation in construction, Ch. 1, in: C. Balaguer, M. Abderrahim (Eds.), Robotics and Automation in Construction, IntechOpen, Rijeka, 2008.
[74] A. Ruggiero, S. Salvo, C.S. Laurent, Robotics in Construction, Worcester Polytechnic Institute, 2016.
[75] A. Balzan, C.C. Aparicio, D. Trabucco, Robotics in construction: state-of-art of on-site advanced devices, Int. J. High-Rise Build. 9 (1) (2020) 95–104, https://doi.org/10.21022/IJHRB.2020.9.1.95.
[76] S. Zhao, Q. Wang, X. Fang, W. Liang, Y. Cao, C. Zhao, L. Li, C. Liu, K. Wang, Application and development of autonomous robots in concrete construction: challenges and opportunities, Drones 6 (12) (2022) 424, https://doi.org/10.3390/drones6120424.
[77] J.C. Mankins, Technology readiness levels, White Paper, April 6 (1995), 1995.
[78] https://clearpathrobotics.com/blog/2021/10/behind-the-robot-hitts-construction-site-monitoring-husky-ugv/. (Accessed 8 October 2021).
[79] A.J. Madsen, The sam100: Analyzing labor productivity, 2019.
[80] S. Pessoa, A.S. Guimarães, S.S. Lucas, N. Simões, 3d printing in the construction industry - a systematic review of the thermal performance in buildings, Renew. Sustain. Energy Rev. 141 (2021) 110794, https://doi.org/10.1016/j.rser.2021.110794.
[81] M. Taylor, S. Wamuziri, I. Smith, Automated construction in Japan, Proceedings of the Institution of Civil Engineers-Civil Engineering, vol. 156, Thomas Telford Ltd, pp. 34–41, https://doi.org/10.1680/cien.2003.156.1.34.
[82] T. Liu, H. Zhou, Y. Du, J. Zhang, J. Zhao, Y. Li, A brief review on robotic floor-tiling, in: IECON 2018-44th Annual Conference of the IEEE, Industrial Electronics Society, IEEE, 2018, pp. 5583–5588.
[83] S. Reichenbach, B. Kromoser, State of practice of automation in precast concrete production, J. Build. Eng. 43 (2021) 102527, https://doi.org/10.1016/j.jobe.2021.102527.
[84] A. Kochan, Robot cleans glass roof of louvre pyramid, Ind. Robot 32 (5) (2005) 380–382, https://doi.org/10.1108/01439910510614637.
[85] https://invertrobotics.com/. (Accessed 24 April 2022).
[86] N. Anudari, Robotics in construction of concrete and masonry structures, Thesis, 2019.
[87] R. Bogue, What are the prospects for robots in the construction industry?, Ind. Robot 45 (1) (2018) 1–6, https://doi.org/10.1108/IR-11-2017-0194.
[88] https://branchtechnology.com/. (Accessed 24 April 2022).
[89] https://www.herrenknecht.com/en/references/referencesdetail/hong-kong-tuen-mun-chek-lap-kok-link/. (Accessed 24 April 2022).
[90] https://cybe.eu/technology/3d-printers/. (Accessed 24 April 2022).
[91] C. Brown, Autonomous vehicle technology in mining: engineering, geology, mineralogy, metallurgy, chemistry, etc., Eng. Min. J. 213 (1) (2012) 30–32.
[92] https://eksobionics.com/ekso-evo/. (Accessed 21 April 2022).
[93] https://www.lidarusa.com/. (Accessed 12 December 2022).
[94] S. Dooley, S. Kim, M.A. Nussbaum, M.L. Madigan, Occupational arm-support and back-support exoskeletons elicit changes in reactive balance after slip-like and trip-like perturbations on a treadmill, Appl. Ergon. 115 (2024) 104178, https://doi.org/10.1016/j.apergo.2023.104178.
[95] H. Cheng, R. Jia, D. Li, H. Li, The rise of robots in China, J. Econ. Perspect. 33 (2) (2019) 71–88, https://doi.org/10.1257/jep.33.2.71.
[96] I. Aaltonen, T. Salmi, Experiences and expectations of collaborative robots in industry and academia: barriers and development needs, Proc. Manuf. 38 (2019) 1151–1158, https://doi.org/10.1016/j.promfg.2020.01.204.
[97] S.S. Kamble, A. Gunasekaran, R. Sharma, Analysis of the driving and dependence power of barriers to adopt industry 4.0 in Indian manufacturing industry, Comput. Ind. 101 (2018) 107–119, https://doi.org/10.1016/j.compind.2018.06.004.
[98] A.I. Ugochukwu, P.W.B. Phillips, Technology Adoption by Agricultural Producers: A Review of the Literature, Springer International Publishing, Cham, 2018, pp. 361–377.
[99] E.M. Rogers, A. Singhal, M.M. Quinlan, Diffusion of Innovations, Routledge, 2014, pp. 432–448.
[100] A. Raj, G. Dwivedi, A. Sharma, A.B. Lopes de Sousa Jabbour, S. Rajak, Barriers to the adoption of industry 4.0 technologies in the manufacturing sector: an inter-country comparative perspective, Int. J. Prod. Econ. 224 (2020) 107546, https://doi.org/10.1016/j.ijpe.2019.107546.
[101] D. Kiel, C. Arnold, K.-I. Voigt, The influence of the industrial internet of things on business models of established manufacturing companies – a business level perspective, Technovation 68 (2017) 4–19, https://doi.org/10.1016/j.technovation.2017.09.003.
[102] M. Breunig, R. Kelly, R. Mathis, D. Wee, Getting the most out of industry 4.0, McKinsey Global Institute, 2016.
[103] D. Horváth, R.Z. Szabó, Driving forces and barriers of industry 4.0: do multinational and small and medium-sized companies have equal opportunities?, Technol. Forecast. Soc. Change 146 (2019) 119–132, https://doi.org/10.1016/j.techfore.2019.05.021.

[104] M. van Sante, European builders frontrunners in robotics, https://think.ing.com/articles/european-builders-frontrunners-in-robotics/, June 2019.
[105] Q. Chen, B. García de Soto, B.T. Adey, Construction automation: research areas, industry concerns and suggestions for advancement, Autom. Constr. 94 (2018) 22–38, https://doi.org/10.1016/j.autcon.2018.05.028.
[106] P.S. Mistri, H.A. Rathod, Remedies over barriers of automation and robotics for construction industry, Int. J. Adv. Res. Eng. Sci. Manag. (2015) 1–4.
[107] Z. Zhu, A. Dutta, F. Dai, Exoskeletons for manual material handling – a review and implication for construction applications, Autom. Constr. 122 (2021) 103493, https://doi.org/10.1016/j.autcon.2020.103493.
[108] R. Bogue, Exoskeletons: a review of recent progress, Ind. Robot 49 (5) (2022) 813–818, https://doi.org/10.1108/IR-04-2022-0105.
[109] I. Halim, A. Saptari, Z. Abdullah, P. Perumal, M.Z. Zainal Abidin, M.N. Muhammad, S. Abdullah, Critical factors influencing user experience on passive exoskeleton application: a review, Int. J. Integr. Eng. 14 (4) (2022) 89–115, https://doi.org/10.30880/ijie.2022.14.04.009.
[110] W. Tang, M. Qiang, F. Duffield Colin, M. Young David, Y. Lu, Incentives in the Chinese construction industry, J. Constr. Eng. Manag. 134 (7) (2008) 457–467, https://doi.org/10.1061/(ASCE)0733-9364(2008)134:7(45.
[111] HM Government, Industrial strategy: Construction sector deal, HM Government: UK, 2018.
[112] https://ec.europa.eu/info/research-and-innovation/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-2020_en. (Accessed 20 April 2022).
[113] B. Arad, J. Balendonck, R. Barth, O. Ben-Shahar, Y. Edan, T. Hellström, J. Hemming, P. Kurtser, O. Ringdahl, T. Tielen, B. van Tuijl, Development of a sweet pepper harvesting robot, J. Field Robot. 37 (6) (2020) 1027–1039, https://doi.org/10.1002/rob.21937.
[114] E. Cronin, A. Fieldsend, E. Rogge, T. Block, Multi-actor horizon 2020 projects in agriculture, forestry and related sectors: a multi-level innovation system framework (minos) for identifying multi-level system failures, Agric. Syst. 196 (2022) 103349, https://doi.org/10.1016/j.agsy.2021.103349.
[115] https://ec.europa.eu/research-and-innovation/en/projects/success-stories/all/harder-better-faster-stronger-cleaner-composites-greener-cars. (Accessed 21 April 2022).
[116] E.S. Kirby, China's first five-year plan, J. R. Cent. Asian Soc. 42 (3–4) (1955) 269–274, https://doi.org/10.1080/03068375508731554.
[117] S. Kennedy, C.K. Johnson, Perfecting China, Inc.: China's 13th Five-Year Plan, Rowman & Littlefield, 2016.
[118] J. Casey, K. Koleski, Backgrounder: China's 12th five-year plan, US-China Economic and Security Review Commission Washington, DC, USA, 2011.
[119] B. Dellot, F. Wallace-Stephens, What's stopping UK businesses from adopting ai & robotics? 2017.
[120] S. Adam, I. Delestre, V. Nair, Corporation Tax and Investment, Institute for Fiscal Studies, 2022.
[121] S. Bray, Corporate tax rates around the world, 2021, Tax Found. 9 (2021) 2021.
[122] B. Li, A. Akintoye, An overview of public-private partnership, in: Public-private partnerships: Managing risks and opportunities, 2003, pp. 3–30.
[123] https://www.gov.uk/government/publications/construction-2025-strategy, 2013.
[124] N.C.Y. Yeo, H. Pepin, S.S. Yang, Revolutionizing technology adoption for the remanufacturing industry, Proc. CIRP 61 (2017) 17–21, https://doi.org/10.1016/j.procir.2016.11.262.
[125] K. Ridgway, C.W. Clegg, D. Williams, P. Hourd, M. Robinson, L. Bolton, K. Cichomska, J. Baldwin, The factory of the future, Government Office for Science, Evidence Paper 29, 2013.
[126] EFFRA, Progress monitoring report for 2017, Report, Factories of the Future: Public Private Partnership, 2017.
[127] D. Boothby, A. Dufour, J. Tang, Technology adoption, training and productivity performance, Res. Policy 39 (5) (2010) 650–661, https://doi.org/10.1016/j.respol.2010.02.011.
[128] L. Agostini, A. Nosella, The adoption of industry 4.0 technologies in smes: results of an international study, Manag. Decis. 58 (4) (2020) 625–643, https://doi.org/10.1108/MD-09-2018-0973.
[129] D. Castro-Lacouture, Construction Automation, Springer Berlin Heidelberg, Berlin, Heidelberg, 2009, pp. 1063–1078.
[130] M. Pan, T. Linner, W. Pan, H. Cheng, T. Bock, Structuring the context for construction robot development through integrated scenario approach, Autom. Constr. 114 (2020) 103174, https://doi.org/10.1016/j.autcon.2020.103174.
[131] D. Palka, J. Brodny, K. Stecuła, Modern means of production and the staff awareness of the technical in the plant of the mining industry, in: CBU International Conference Proceedings, vol. 5, 2017, pp. 1190–1194.
[132] D. Sabourin, et al., Skill Shortages and Advanced Technology Adoption, Citeseer, 2001.
[133] J.P. Gander, Technology adoption and labor training under uncertainty, Econ. Educ. Rev. 22 (3) (2003) 285–289, https://doi.org/10.1016/S0272-7757(02)00035-3.
[134] G. Brunello, P. Wruuck, Skill shortages and skill mismatch: a review of the literature, J. Econ. Surv. 35 (4) (2021) 1145–1167, https://doi.org/10.1111/joes.12424.
[135] https://www.gov.uk/guidance/digital-skills-partnership. (Accessed 24 January 2022).
[136] Department for Digital, Culture, Media and Sport, Evaluation of the local digital skills partnerships, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1021163/Evaluation_of_LDSP_final_report_270921.pdf, 2021.
[137] M. Wang, C.C. Wang, S. Sepasgozar, S. Zlatanova, A systematic review of digital technology adoption in off-site construction: current status and future direction towards industry 4.0, Buildings 10 (11) (2020) 204, https://doi.org/10.3390/buildings10110204.
[138] R. Roberts, R. Flin, D. Millar, L. Corradi, Psychological factors influencing technology adoption: a case study from the oil and gas industry, Technovation 102 (2021) 102219, https://doi.org/10.1016/j.technovation.2020.102219.
[139] G. Premkumar, M. Roberts, Adoption of new information technologies in rural small businesses, Omega 27 (4) (1999) 467–484, https://doi.org/10.1016/S0305-0483(98)00071-1.
[140] E. Gibson, T.U. Daim, M. Dabic, Evaluating university industry collaborative research centers, Technol. Forecast. Soc. Change 146 (2019) 181–202, https://doi.org/10.1016/j.techfore.2019.05.014.
[141] D. Roessner, Outcomes and impacts of the state/industry-university cooperative research centers (s/iucrc) program, Final Report, SRI International, 2000.
[142] J. Wübbeke, M. Meissner, M.J. Zenglein, J. Ives, B. Conrad, Made in China 2025, Papers on China 2 Mercator Institute for China Studies, 2016, p. 74.
[143] F.G. Pratticò, F. Lamberti, Towards the adoption of virtual reality training systems for the self-tuition of industrial robot operators: a case study at kuka, Comput. Ind. 129 (2021) 103446, https://doi.org/10.1016/j.compind.2021.103446.
[144] https://builduk.org/. (Accessed 1 August 2022).
[145] http://www.chqy.org/. (Accessed 1 August 2022).
[146] J. Mayer, Robots and industrialization: What policies for inclusive growth? Growth and Reducing Inequality, Working Paper Series, 2018, https://doi.org/10.13140/RG.2.2.35211.75048.
[147] R. Mahbub, An investigation into the barriers to the implementation of automation and robotics technologies in the construction industry, Thesis, 2008.
[148] 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.
[149] R. Sparrow, M. Howard, Robots in agriculture: prospects, impacts, ethics, and policy, Precis. Agric. 22 (3) (2021) 818–833, https://doi.org/10.1007/s11119-020-09757-9.
[150] M.A. Kamarul Bahrin, M.F. Othman, N.H. Nor Azli, M.F. Talib, Industry 4.0: a review on industrial automation and robotic, J. Teknol. 78 (6–13) (2016), https://doi.org/10.11113/jt.v78.9285.
[151] G. Graetz, G. Michaels, Robots at work, Rev. Econ. Stat. 100 (5) (2018) 753–768, https://doi.org/10.1162/rest_a_00754.

[152] https://www.gov.uk/government/publications/robotics-and-autonomous-systems-the-economic-impact-across-uk-sectors-2021. (Accessed 11 December 2021).
[153] R. Hu, K. Iturralde, T. Linner, C. Zhao, W. Pan, A. Pracucci, T. Bock, A simple framework for the cost-benefit analysis of single-task construction robots based on a case study of a cable-driven facade installation robot, Buildings 11 (1) (2020) 8, https://doi.org/10.3390/buildings11010008.
[154] http://www.moa.gov.cn/xw/zxfb/202105/t20210510_6367489.htm. (Accessed 11 December 2022).