Stakeholder Perceptions of the Future Application of Construction Robots for Buildings in a Dialectical System Framework

Mi Pan, Wei Pan

DOI: https://doi.org/10.1061/(ASCE)ME.1943-5479.0000846

To appear in: Journal of Management in Engineering

Please cite this article as: Pan, M., Pan, W. (2020). Stakeholder Perceptions of the Future Application of Construction Robots for Buildings in a Dialectical System Framework. *Journal of Management in Engineering*, 36(6), 04020080. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000846.

Stakeholder perceptions on the future application of construction robots for buildings in a dialectical system framework

Mi Pan, Ph.D.[1] and Wei Pan, Ph.D.[2]

[1]Postdoctoral Fellow, Department of Civil Engineering, The University of Hong Kong, Pokfulam, Hong Kong, Hong Kong SAR, China (corresponding author). Email: panmi@connect.hku.hk

[2]Associate Professor, Department of Civil Engineering, The University of Hong Kong, Pokfulam, Hong Kong, Hong Kong SAR, China. Email: wpan@hku.hk

Abstract

Construction robots have many promises for buildings, but their real-world up-take is limited. Previous studies lacked in-depth explorations of stakeholder perceptions to help elaborate development requirements and dialectics of construction robots. This paper aims to examine stakeholder perceptions of future construction robots for buildings within the Hong Kong context theoretically based on a dialectical system framework that incorporates the technical systems, stakeholders, and contexts. The study was conducted through a questionnaire survey with wide-ranging industry stakeholders that yielded 166 effective responses and 20 follow-up interviews for generating insights. The results indicate that construction robots have minimal applications but are perceived to be important, particularly in off-site production and onsite lifting. The findings reveal the multi-dimensional complexity of task-oriented technical systems and influencing contexts of construction robots and demonstrate their dialectical relationship. Recommendations are offered for promoting robot applications, which include leveraging government support, capitalizing on off-site construction, encouraging technology adaptation, and driving task-technology integrative and iterative design. This paper contributes to the literature on construction robotics by proposing a novel dialectical system framework and providing new insights for future research and development.

Keywords: construction robot; building; technological innovation; future planning; stakeholder; dialectical system

Introduction

Robots are smart machines that are programmable to perform tasks automatically, which has triggered a wide spectrum of research themes in both well-engineered industrial workplaces and domain-oriented applications operating in hazardous and/or harsh environments (Siciliano and Khatib, 2016). As for the construction industry, research and development (R&D) efforts have been conducted on a wide range of robotic technologies for different construction tasks (Bock and Linner 2016), demonstrating the potential benefits of robots in continuously enhancing the quality, productivity, safety and sustainability of building construction. The application of construction robots also relates to the integration of corresponding technologies and systems such as smart sensing systems, building information modeling (BIM), internet of things (IoT), virtual reality (VR), and artificial intelligence, which have been widely promoted to reshape the construction industry (Bock 2015; Shen and Lu 2012; World Economic Forum 2018; Wu and Issa 2014). However, the real-world up-take of construction robots is still limited, and the industry is seemingly to be conservative in, and generally poorly prepared for, adopting these technologies. The broad utilization of construction robots could be an important driving force for industrial transformation (Yang et al., 2019), thereby necessitating a clear understanding of the prospects and impacts of construction robot applications.

Some previous studies attempted to explore the underlying barriers to and potential drivers for the utilization of construction robots. For example, Mahbub (2008) examined and analyzed the barriers to the implementation of automation and robotics technologies in the construction industry. Delgado et al. (2019) investigated industry-specific challenges facing the adoption of construction automation and robotics in terms of contractor-side economic factors, client-side economic factors, technical and work-culture factors, and weak business case factors. There are also increasing researchers (e.g., Agustí-Juan et al. 2017; Pan et al. 2018; Yeon et al. 2020) explored and argued sustainable benefits of construction robot applications that could potentially drive future practices. Despite insightful findings from previous works, there is a lack of studies exploring stakeholder perceptions on the future application of different construction robots within diverse socio-technical contexts in a systems manner. An in-depth understanding of stakeholder perceptions is essential to elaborate development requirements of construction robots for effective application. Evidence can be found in the literature of other construction innovations and technologies. For instance, the sources of innovation in construction are often widely spread among the stakeholders across the value chain (Slaughter 2000). The lack of early engagement of and knowledge exchange among stakeholders (Pan and Pan 2018), as well as resistance of stakeholders to change (Chan et al. 2017), are critical barriers to implementing innovation in the construction industry. It has also been argued that technology is not the real determining factor to hinder successful innovation adoption; instead, organizational and procedural difficulties embedded in the adoption are critical (Häkkinen and Belloni 2011; Wu and Issa 2014). The potential of construction robots to drive transformation in the construction industry is more than a technical issue per se but is highly linked to stakeholder engagement (Zhou et al. 2018) and complex contexts (Pan et al. 2020), which together feature the dialectics of robot application.

Therefore, this paper aims to examine stakeholders' understanding and practices of, and explore their perceptions on, the future application of construction robots for buildings. The examination was conducted by applying the dialectical system theory within the context of Hong Kong as a typical high-density city. The dialectical system framework developed by Pan and Pan (2018) was adapted as a theoretical basis to highlight the interactions between the technical components, stakeholders, and contexts characterizing the application of construction robots. The research is based on an industry-wide survey combining a questionnaire and follow-up interviews, which involved professionals from six industry stakeholder groups highly relevant to construction robots in Hong Kong. The dialectical approach is for the first time applied to the construction robot field. The findings contribute an in-depth understanding of stakeholder perceptions on construction robots, confirm the effectiveness and applicability of the dialectical system framework in guiding construction robot research and practices, and provide theoretical and practical insights into technology application in the construction industry.

The remainder of this paper is structured as follows. The research background and context are introduced in the next section, followed by the outline of the research methods, including the research design, sampling strategy, and methods for data collection and analyses. The paper then presents the survey results and analyses, and discusses the findings to provide conceptual, theoretical and practical insights into the future application of construction robots. The final section concludes the paper and suggests future research directions.

Background of research

Terms and definitions of construction robots

The science and engineering of robots appear to present a wide spectrum of research themes in both well-engineered industrial workplaces and domain-oriented applications (Siciliano and Khatib 2016). The International Organization for Standardization (ISO 2012) defines a robot as "*an actuated mechanism programmable in two or more axes with a degree of autonomy, moving within its environment, to perform intended tasks*", and classifies it into industrial robot and service robot according to whether or not the robot is for industrial automation applications.

As for the construction field, a consensus has not yet been made on a clear definition for a construction robot (Pan et al. 2018). Scholars have proposed diverse definitions of "construction automation", "construction robotics", or "construction robot". The terms often overlap in use, but most can be encapsulated in systems from mechanical machinery manipulated by a human operator, to semi-automated or automated devices with remote control, to autonomous robots with more sensible and intelligent characteristics (Pan et al. 2018). Table 1 presents the relevant definitions of construction robots from the reviewed literature and ISO. Most of the definitions of construction robots integrate the mechanical features of robots and construction characteristics in terms of task and site. Based on ISO (2012) and relevant terms described in the literature, this present paper defines a construction robot as *an actuated mechanism programmable in two or more axes, with a degree of autonomy, which can be either fixed in place or mobile, to perform construction tasks which normally ascribed to humans*. The terms "construction robotics" and "construction robotic technology" mainly refer to the science and practice of designing, producing and applying construction robots.

[insert Table 1 here]

Worldwide applications of construction robots for buildings

Automation and robotics are increasingly recognized as most promising solutions to addressing the multifaceted challenges confronting the construction industry, and as advanced techniques to underpin the "production" of buildings (Pan et al. 2018). Many early applications of construction robots were seen in off-site production, followed by many on-site single-task prototype robots to alleviate the labor shortage problem, such as mobile handling robots, concrete finishing robots, plastering robots, fireproofing robots, and demolition robots, as well as full-scale on-site automated construction system (Linner 2013; Bock and Linner 2016). In recent years, there have been expanding and accelerating research and development on construction robot applications, such as in additive manufacturing (Izard et al. 2018), on-site building elements fabrication (Giftthaler et al. 2017), bricklaying and glazing (Bogue 2018), building facade install, repairs and maintenance (Taghavi et al. 2018), robotic exoskeletons for construction workers (Linner et al. 2018), and aerial robots for different construction application scenarios (Zhou et al. 2018). Furthermore, robots offer great opportunities to facilitate other construction innovations, such as digitalization. For example, intelligent or robotic bulldozers, incorporated by various digital systems and equipped with intelligent machine-control systems, enable the autonomy of pre-foundation work (World Economic Forum 2018). LIDAR (light detection and ranging), sometimes known as three-dimensional (3D) laser scanning, has been widely applied with robotic drones and vehicles for digitalized site surveying, inspection, and monitoring (Wang et al. 2015; Li and Liu 2019).

Despite trials or initial applications, many of these innovative robots are still discussed as a future technology that lacks real-world adoption (World Economic Forum 2018). The role of these technologies is deemed to assist in conducting dangerous, monotonous or tedious construction tasks in a more safe, efficient and accurate way, but also regarded as a hefty investment with little economic interest due to high capital costs and additional set-up time (Bock and Linner 2016). Such complexity presents interrelated challenges and opportunities (Delgado et al. 2019; Pan et al. 2020), and further illustrates the system dialectics in the application of construction robots.

The context of the Hong Kong construction industry

In Hong Kong, the construction industry is confronting critical challenges such as the aging workforce and labor shortage, lack of innovation, cost escalation, unsatisfactory quality and safety performance (Development Bureau 2018), where robotics is one of the most promising solutions (Linner et al. 2018). Although the industry is generally unfamiliar with construction robots, there are emerging attempts and initiatives. Major local construction companies are progressively investing in innovative technologies such as robotic arms for lifting heavy construction materials, exoskeletons for worker support, and 3D printing (Gammon 2017), which hugely invigorate and inspire the remaining of the industry. There are also emerging startups focusing on robot applications for building sites such as site surveillance and recording, spray painting, and automated floor tiling (Lan and Fu 2019).

Meanwhile, the government has provided the industry continuous financial and non-financial supports to create a more fertile environment for innovation and technology R&D (Chief Executive 2018). The Construction Industry Council (CIC) launched the Construction Innovation and Technology Application Centre in 2017 to accelerate information sharing and practices on the latest construction technologies (CIC 2017). The center has exhibited a variety of automated and robotic technologies for the construction industry, such as a multi-functional facade and exterior finishing robot, drones for inspection, automated plastering machines, and rail climbing systems. Furthermore, the Hong Kong Institute of Construction was established in 2018 to cultivate higher caliber and professional practitioners for the construction industry (Chief Executive 2018).

A dialectical system framework for the application of construction robots

Systems theory or systems thinking has been widely applied to address the challenging complexity of modern construction (Sackey et al. 2014; Pan and Pan 2018). A “system” is defined as a construct or collection of different components or elements that together produce results that are unobtainable by the elements alone (NASA 2007). The dialectical approach has been effectively applied to management fields and innovation studies to address complex systems and the interdependence of the elements. In particular, the dialectical system theory developed in Pan and Ning (2015) and Pan and Pan (2018) emphasizes the system complexity and interdependence embracing multifaceted and interwoven dialectics in understanding complex systems. It thus can be used to address the intricate problems regarding the application of construction robots. Drawing on the dialectical system theory (Pan and Ning 2015; Pan and Pan 2018), a dialectical system framework is redeveloped for this present paper (Fig. 1). This framework, as explained below, theoretically illustrates the multi-dimensional complexities and interdependency of construction robot application, in terms of the technical systems, stakeholders, and different influencing contexts.

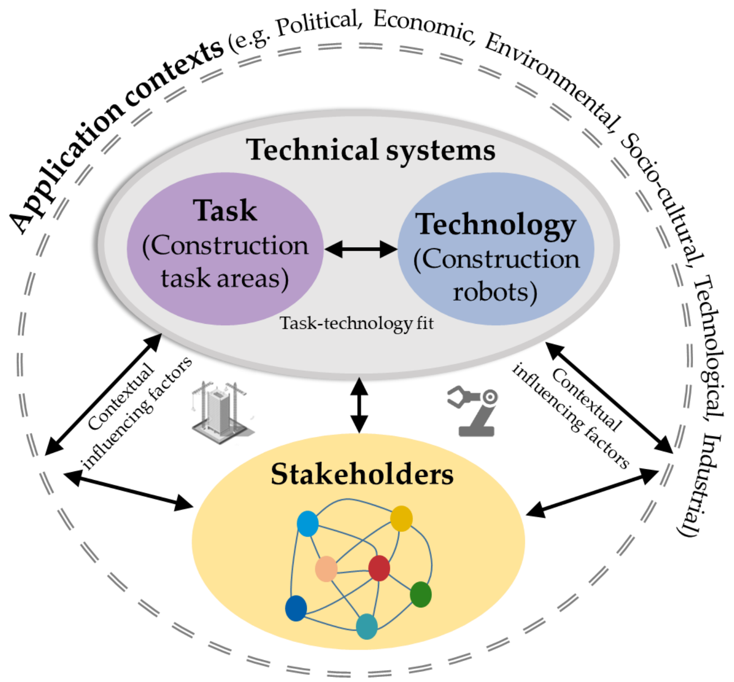

Fig. 1. A dialectical system framework for the application of construction robots

Firstly, the framework defines the technical systems as task-technology systems considering that the match between the complex application/task areas for building works and diversified construction robots is a fundamental concern for construction robot utilization (Linner et al. 2018). The applications of construction robots, while are mostly organizational level decisions, essentially hinge on the fitness or appropriateness between task and technology (Linner et al. 2018). The importance of the fitness between the technology and the associated task is also emphasized by the task-technology fit theory (Zigurs and Buckland 1998) in the broad field of technology management. In addition, the task-oriented design is the mainstream of practice in traditional construction robot development (Bock and Linner 2016). Thus, robot applications for specific construction tasks could have different limitations and prospects (Delgado et al. 2019) that worthwhile for a systematic exploration to guide both future research and practices.

Secondly, the framework highlights that construction robot utilization could affect and be affected by stakeholder groups across the supply chain. Stakeholders can positively drive or prevent innovation attempts (Widén et al. 2013). Dispersed actors or stakeholders with divergent interests in the built environment pose significant difficulties for innovation and changes (Whyte and Sexton 2011). There is always a plurality of negotiations and alignments among different parties within the implementation of innovative technologies in the construction industry (Harty 2008). Stakeholder engagement is also essential for innovation adoption from the change management perspective (Kotter 2012; Erdogan et al. 2014). The consideration of different stakeholders and their roles (Zhou et al. 2018; Delgado et al. 2019; Pan et al. 2020) is, therefore, of major importance to examine construction robot application.

Thirdly, the framework denotes that the application of construction robots is influenced by the broader socio-technical or socio-ecological contexts of the built environment. Construction innovations are changes to complex systems, involving changes to the context of systems and innovation itself to better fit each other (Slaughter 2000). The contextual requirements, conditions, and disparities are critical concerns for construction innovation (Harty 2008) and need to embrace multiple perspectives in the analysis (Whyte and Sexton 2011). In this regard, the economic, environmental, industrial, political, socio-cultural, and technological contexts (Pan et al., 2020) that could influence future construction robots should be examined with task-oriented robot applications.

Research Methods

Research design

This research was conducted through the combination of a questionnaire survey with wide-ranging industry stakeholders and follow-up interviews. Six key stakeholder groups (i.e., contractors; developers, clients and investors; professional advisors; government and its agencies; manufacturers and suppliers; and universities and professional bodies) are determined for the research, as most highlighted in studies of construction robotics (e.g., Pan et al. 2020) or other technological innovation adoption in the construction industry (e.g., Pan and Pan, 2018). There are overlapping roles among different groups, but only the primary area of practice is considered for choosing the stakeholder group of an organization. Contractors (including main and sub-contractors) are main adopters for construction robots. Developers, clients and investors are those key decision-makers for robot uptake in real-world building projects. Professional advisors include architects, designers, engineers, planners, surveyors that are critical to building design and innovation, which might affect, or be affected by, the use of construction robots. The government and its agencies are critical to the regulation and motivation of innovation (e.g., robotics) application and industry operation. Manufacturers and suppliers group are important to the supply chains of building projects that might be reconfiguration by the introduction of construction robotics. Universities and professional bodies are critical to R&D and professional training regarding construction robots.

Drawing on the dialectical system framework (Fig.1), the questionnaire survey aimed to empirically examine stakeholders' understanding and practices of, and explore their perceptions on, the application of construction robots for buildings. Based on the literature findings (e.g., Linner et al. 2018; Pan et al. 2020), the questionnaire was designed to include questions regarding information on participants, knowledge on and experiences in construction robots, perceptions on technical systems (task/application areas) for the future application of construction robots for buildings, and on different influencing contexts (influencing factors) for the future application. In particular, a number of task areas were defined according to major building works in Hong Kong [Hong Kong Special Administration Region (HKSAR) Government 2017; Linner et al. 2018]. The influencing contexts and influencing factors were initially determined, referring to previous works on construction robots (Pan et al. 2020). The follow-up interviews aimed to reveal insights into the stakeholder perceptions and attitudes, and verified the responses to, and the results of the questionnaire survey. The interview questions were based on the questionnaire but focused more on seeking explanatory answers.

Research sampling

The questionnaire survey participants were selected via multistage sampling. The participants were first classified using a stratified sampling strategy (Fellows and Liu 2015). In doing so, professionals were targeted from six key stakeholder groups. Next, potential survey participants were identified under stakeholder groups using publicly available databases supplemented by the networks of the researchers and their affiliated institutions. Hong Kong's building and construction industry is characterized by a small group of large-sized main contractors and a large number of small and medium-sized subcontractors, with a substantial proportion of companies being both contractors and developers (Pan et al. 2020). The contractor is thus the most important stakeholder group in this research. Examples of the accessed publicly available databases of stakeholders included: Development Bureau's (2017) list of approved contractors, Building Department's (2017) list of registered contractors and Hong Kong Trade Development Council's (2017) database of contractors, The Hong Kong Institution of Engineers list of professionals, Hong Kong Real Estate Developers Association's (2016) list of developers. Finally, the survey participants were selected from each strata using random sampling (Fellows and Liu 2015). The overall process yielded a sample of 1500 professionals invited to the survey.

The interview participants were identified and selected from the survey participants who were willing to participate in a follow-up interview. The stratified sampling strategy was adopted for the selection to ensure that the interviewees covered the six identified key stakeholder groups.

Data collection and analyses

The questionnaire survey was carried out via the combined use of a cover email with an editable PDF file attached and a web link for an electronic version of the questionnaire to be filled in online. This strategy helped to ensure an effective response rate and maximize stakeholder engagement. The participants were asked to give their views based on a 5-point Likert scale and provide additional comments. The interviews, each lasting about 30 minutes, were conducted in person or through telephone. The interviews were audio-recorded with the permission of participants, and then transcribed. Transcriptions and notes were logged and coded for analysis.

The quantitative data were converted using SPSS software for descriptive and statistical analyses. The standard deviations were calculated to illustrate the degree of difference among the respondents. The relative importance index (RII) method (Ghosh and Jintanapakanont 2004) was used for ranking variables or items. A higher RII value means a higher perception of the survey participants on the target item. The one-way analyses of variance (ANOVA) tests were applied to assess the statistical consistency of the perceptions from different stakeholder groups. The exploratory factor analysis (EFA) was conducted using the principal component method with varimax rotation (Costello and Osborne 2005) on the items of technical systems and contexts to reduce the dimensions of the derived task factors and contexts of future construction robot application. There are a number of criteria and guidelines for EFA to assess the data suitability, factor selection, reliability (Hair et al. 2010). The Measure of Sampling Adequacy (MSA) that should be higher than 0.5 and Bartlett Test of Sphericity that should be significant ($p<0.05$) were conducted to assess the suitability of the collected data for EFA. Items with communality higher than 0.5 and factor loading greater than ±.50 but not cross-loaded significantly are considered practically significant. The reliability of the extracted factors was assessed by Cronbach's α, considering the satisfactory value above 0.7. Summated scales were computed after EFA to replace the original set of items for subsequent analyses. Summated scales is more suitable than surrogate variables and factor scores to portray complex concepts using a single measure, in terms of reducing measurement, error generalizability and transferability (Hair et al. 2010). The reliability could be Pearson's correlation coefficients were calculated to evaluate relationship (correlation) between extracted dimensions.

Analysis Results

The questionnaire survey approached 1500 informed stakeholders in the Hong Kong building industry and society. In total 169 questionnaires were returned, of which 166 were properly completed, yielding an overall effective response rate of 11.1%, which is comparable to other studies as an internet-based survey in the construction field (Pan and Pan 2018). Semi-structured interviews were conducted with 20 selected professionals from the questionnaire survey, who expressed their willingness to participate in the follow-up interviews, to further reveal insights into the stakeholders' perceptions and verify the results of the questionnaire survey.

Profile of research participants

The profiles of the questionnaire survey participants are summarized in Fig. 2. The participants, through their primary organizational affiliations, effectively covered the six key stakeholder groups related to the use of construction robots in the Hong Kong building sector. The groups were (1) contractors (including main and sub-contractor) (49.4%), (2) developers, clients and investors (7.8%), (3) professional advisors (16.3%), (4) government and its agencies (9.6%), (5) manufacturers and suppliers (7.8%), and (6) universities and professional bodies (9%). More than 80% of questionnaire participants had more than 10 years of working experience in the Hong Kong building industry, while more than 60% work for exceed 20 years. More than 70% of questionnaire participants are from the senior management level, and those qualified individuals indicate good quality of data and ensure a reliable result of how construction robots have been used and perceived. Semi-structured interviews were conducted with 20 informed professionals, who together covered all the six stakeholder groups (Table 2).

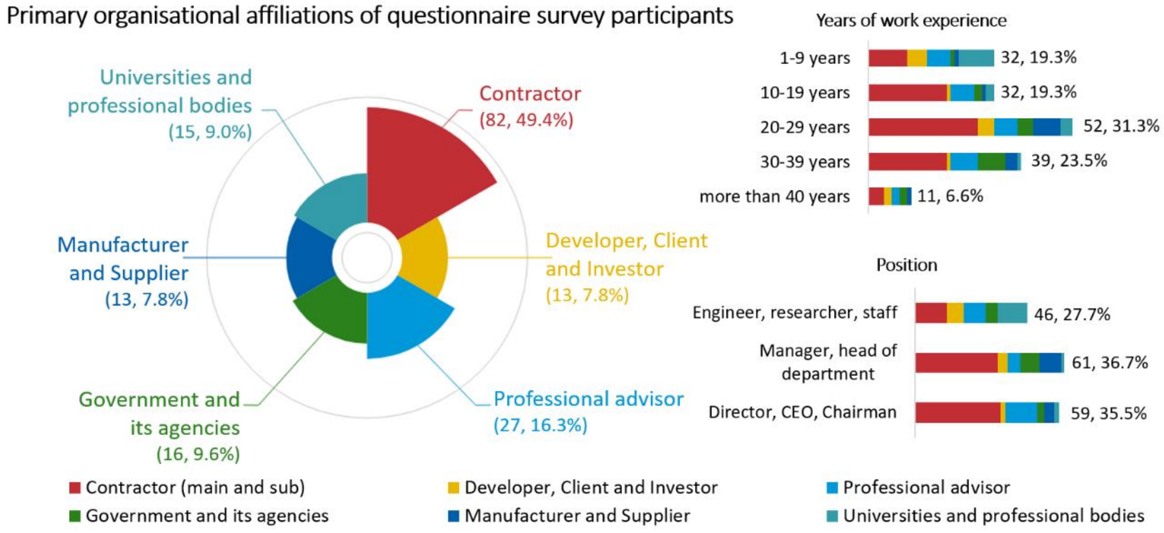

Fig. 2. Primary organizational affiliations, work experience and position of questionnaire survey participants (n=166)

[insert Table 2 here]

Stakeholder's knowledge and experiences of construction robots

Definition of a construction robot

Around two thirds (66.3%) of the questionnaire survey respondents either agreed (47%) or strongly agreed (19.3%) with the proposed definition that *"A construction robot is an actuated mechanism programmable in two or more axes, with a degree of autonomy, which can be either fixed in place or* *mobile, to perform construction tasks which normally ascribed to humans"*. Besides, 27.7% of the respondents held a neutral attitude to the definition provided, and only a small portion of the respondents (6%) disagreed (Fig. 3).

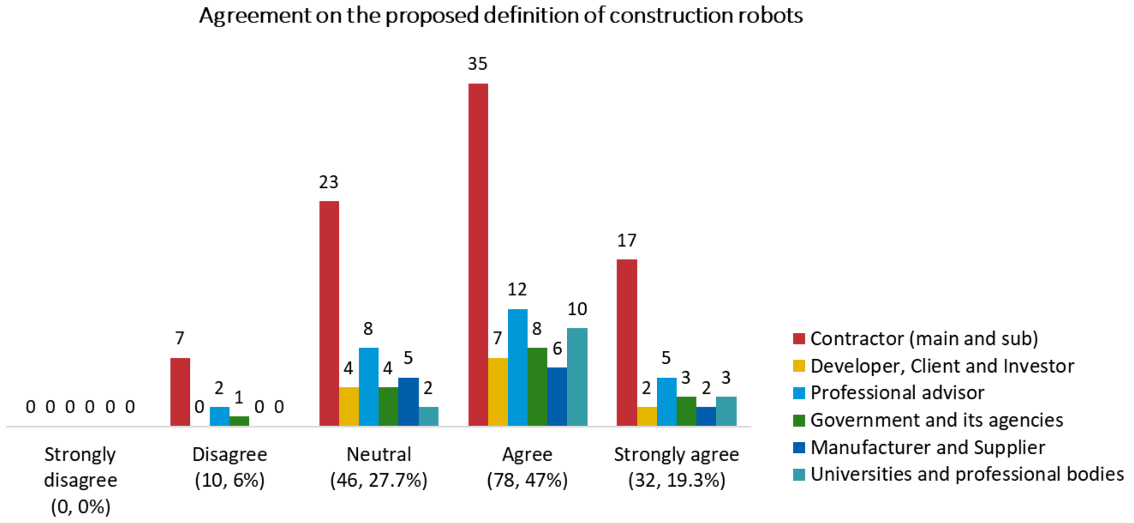

Fig. 3. Perspectives on the proposed definition of construction robots (n=166)

Through analyzing the comments collected in general open questions and the follow-up interviews, the reasons for those neutral and disagreement perceptions on the definition were identified to be: a) limited knowledge and uncertainty toward construction robots; b) consideration of a more general and understandable definition; c) consideration of defining the contribution to achieving objectives rather than constraining the application of new technology to a pre-conception; and d) inclusion of functions of construction robots to perform repetitive tasks as well as enhance productivity and site safety.

Experiences with the use of robots in a building project

Only 19.9% (33) of the respondents indicated that their organization has experience with the use of robots in a real-world building project (Fig. 4). As for each stakeholder group, participants from the group of universities and professional bodies had a relatively higher percentage of use experience than any of the other groups. Those participants who responded to have had experience with robots were also required to specify the area of application. The applications and experiences specified are summarized below with examples in Fig. 4.

- *Off-site applications*: e.g., robots for reinforcement bending, welding robots, and computerized auto cut machines.

- *On-site applications*: e.g., robotic painting, robots for excavation and bricklaying, automated guided vehicles, lifter, robotic gantries, exoskeleton suits, robotic arms for drilling holes, concrete breakers, and demolition robot.
- *Defect checking, inspection and data collection*: e.g., drones, robots for pipe works, robots for checking rendering and surface defects, cracks and uneven surfaces, and water leakage.
- *New applications under development*: e.g., cable robots, collaborative robots, and 3D printing.

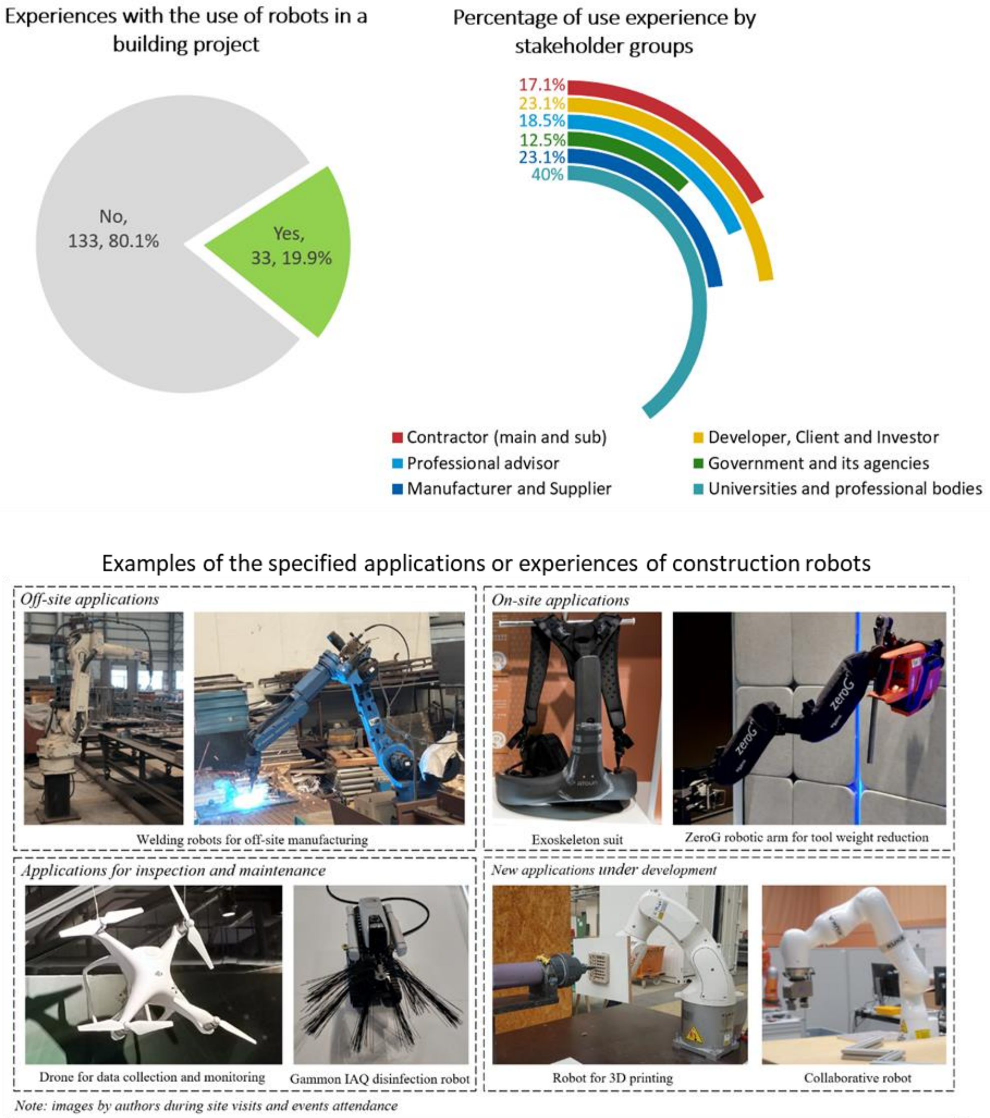

Fig. 4. Experiences (upper) and examples (lower) with the use of robots in a building project (n=166)

This finding is consistent with the result of the literature review that the use of construction robots is limited in the Hong Kong building sector. The follow-up interviews further revealed that many companies are not familiar with, but are quite interested in, construction robots.

Perceptions on technical systems of future application of construction robots

The majority of the questionnaire survey respondents viewed the future need for using construction robots for buildings in Hong Kong as either "very important" (27.7%) or "important" (38.6%), while only 3 (1.8%) participants considered that as "not important" (Fig. 5). The perception on the importance of construction robots by the manufacturers and suppliers group is found to be slightly lower than that by the other stakeholder groups.

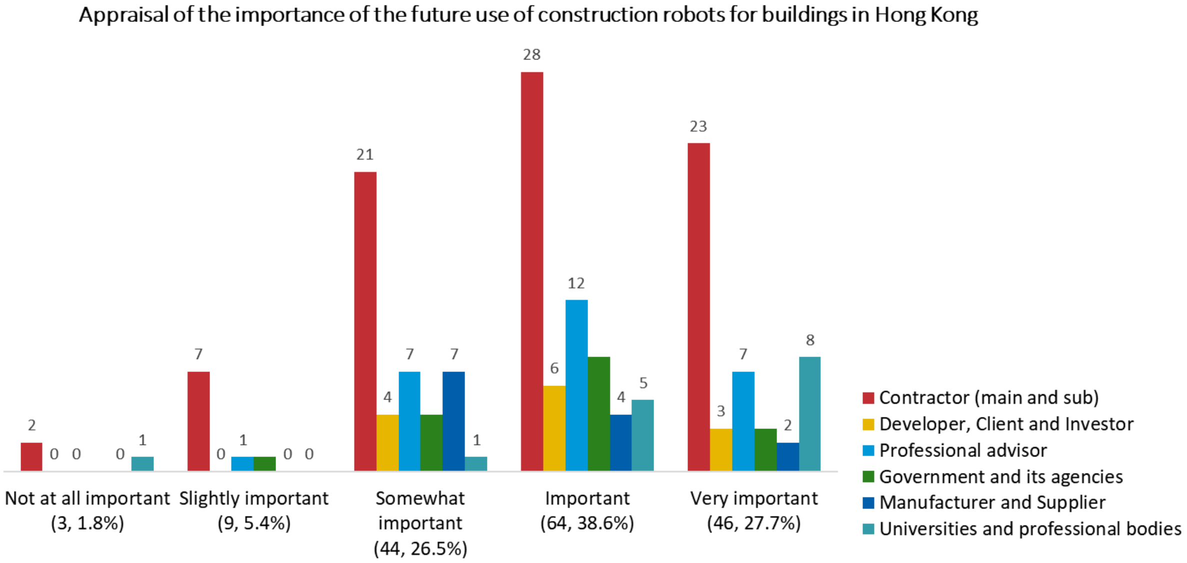

Fig. 5. Appraisal of the importance of the future use of construction robots for buildings in Hong Kong (n=166)

More specifically, the survey examined the importance of construction robots to be applied (assisting or changing existing practices) to potential task areas in building projects in Hong Kong. A list of task/application areas identified from reviewing the literature and regulatory documents (HKSAR Government 2017; Linner et al. 2018) was provided for the examination. Table 3 presents the mean, standard deviation (SD), RII and the corresponding ranking (R), one-way ANOVA tests by the participating stakeholders, and results of the EFA of applying construction robots in different task areas.

Descriptive statistics show that the application of construction robots was perceived as important in most of the examined task areas. As for the ranking, "*off-site production/prefabrication*" was agreed as the most important future application area for construction robots, followed by "*automated/robotic on-site factories*", "*crane and site lifting operation*", "*demolition*" and "*structural steel work in the main structure construction*".

The homogeneity of variance assumption for ANOVA tests were violated ($p < 0.05$) in three variables (task areas) for the test between stakeholder groups. As for the remaining variables, the ANOVA test revealed F-probability of significance at 0.05 level on two variables ("*crane and site lifting operation*", "*building renovation and fitting-out*"). These findings indicate that the opinions among the different stakeholders are generally not statistically significantly different from each other. From the Post Hoc Tests, the significant differences for both variables were found to only exist between the group of universities and professional bodies and others.

The EFA of the 22 task areas extracted seven dimensions, explaining 79% of the variance. Two task areas ("*site operation – scaffolding*" and "*general assistance*") did not satisfy the communality and factor loading criteria and one task area ("*metal work*") did not rationally fit with other items in the same factor, and therefore were deleted. Seven dimensions representing the technical systems were named as groundworks, site operation, main structure construction, building services and finishing works, maintenance and renovation, factory-based production, and demolition works. The MSA is 0.886 and the Bartlett Test of Sphericity is significant ($p<0.01$). Cronbach's α is 0.931 for the whole scale, and is over 0.7 for each dimension, indicating the acceptable reliability.

[insert Table 3 here]

Through the follow-up interviews, it was found that all the interviewees considered "*automated/robotic on-site factories*" as the transformation of the off-site production line from off-site factories to or near the construction site. When knowing that it is used to describe complete and integrated on-site automation systems to enable the factory-like environment set-up at the construction sites, many interviewees considered this application is not feasible in the foreseeable future. It has safety concerns and site feasibility issues, and could disruptively change the whole construction system. This again highlights the perceived importance of robots in off-site construction, while the temporary near-site factories might be possible in the future.

Besides, the interviewees also expressed their great interest in exoskeletons that can empower and support human workers. One director of a small contractor commented: "*If only use exoskeletons for protection, I do not think it would become famous in the industry. However, if use exoskeletons for power enhancement, it will be welcome as workers need to pick up materials every day. We also provide some protection devices for workers, but they do not like to use them as they feel that using those devices is inconvenient for them to work.*"

Beyond these two task areas, the interviewees generally agreed on the perceived importance of other areas. Therefore, the perceived most important future application areas are the off-site construction, cranes and site lifting operation, and demolitions, involving specific robots (e.g., welding robots for manufacturing, formwork robots, demolition robots) or upgraded robotic equipment (e.g., automatic unmanned cranes, gantry robots).

Perceptions on influencing contexts of future application of construction robots

The study then evaluated the perceived influence of factors in different influencing contexts that could affect future construction robots for buildings. Examined were 25 influencing factors identified from reviewing the literature and documents in the economic, environmental, industrial, political, socio-cultural and technological contexts (Pan et al. 2020).

The results are presented in Table 4. Judged by the mean values, all the influencing factors were considered to be influential (with mean values larger than 3) to the future development and use of construction robots for buildings in Hong Kong. According to RII and the associated ranking (R), technological and economic areas are perceived as most influential. Notably, "*availability of robotic technology*", "*construction cost*" and "*construction productivity*" are the most influential factors. The ANOVA test results show that there is no significant difference between different stakeholder groups. The EFA of the 25 influencing factors indicated that five dimensions were extracted 65% of the total variance. One influencing factor (globalization in construction) was deleted due to low communality. The results combined influencing factors from the socio-cultural and technological contexts renamed as socio-technological context. The MSA was 0.901 and the Bartlett Test of Sphericity was significant ($p<0.01$). Cronbach's α is 0.928 for the whole scale, and is over 0.7 for each dimension, indicating the acceptable reliability.

[insert Table 4 here]

Through the follow-up interviews, it was also highlighted that the building industry in Hong Kong is generally too conservative and reluctant to changes unless tangible benefits are demonstrated. The government should initiate more specific promotion and incentives for the contractors, such as providing robots to the contractor to compare the use of robots and humans in the same project to understand the attraction and advantages of using robotics. The government invests money in buying the robotic technologies, but without real-case application to show off the benefits and using process, the industry may still not use it. Meanwhile, the interviewees from the government were highlighted the positive attitude from the government. One raised that in Hong Kong Policy Address 2018, the government states to introduce a pro-innovation government procurement policy to raise the technical weighting in tender assessment, in which tenders with innovative suggestions will stand a better chance of winning government contracts. This policy highlights the need of proposing innovative methods in all government procurement and would provide strong support for construction innovation like robotics. The interviewee also supplemented that for building and construction relevant government procurement, the importance of technology and innovation has already been emphasized, with a relatively high marking weighting in the technical tender assessment.

All the influencing factors that were verified through the questionnaire survey and interviews are inclusive and influential to the future utilization of construction robots for buildings in Hong Kong. These factors together indicate the dialectic influence on construction robot applications in the economic, environmental, industrial, political, and socio-technological contexts.

Relationship between technical systems and contexts of the future application of construction robots

Based on the EFA of the technical systems and the contexts of the construction robot application, Table 5 illustrates the statistically significant correlations ($p<0.01$) between the summated scales of technical systems dimensions and the context dimensions. The economic context and socio-technical context were found to strongly or moderately correlate with all technical system dimensions (r>0.3, p<0.01), manifesting the particular importance of economic and socio-technical contexts in shaping construction robot applications. The remaining three contexts were found to have moderate correlations with the dimensions of task areas (r>0.2, p<0.01). The results also indicate insightful findings in terms of different task areas and contexts. For example, "factory-based production" area was found to relatively less correlate with the environmental context (r=0.237, p<0.01), this could be linked to the fact that factory-based production is already an environmentally friendly practice that the further integration of robotics may not be so related to environmental considerations. The results together suggest a complex and dialectical relationship between the technical systems and the contexts of the application of construction robots.

[insert Table 5 here]

Discussion

Knowledge management of construction robots

Construction robots continue to be an emerging theme in the research domain of construction engineering and management. The findings disclose that construction robots have minimal relevant application and poorly understood by the practitioners in the Hong Kong building sector. The ignorance or lack of a common understanding of innovations hinders innovation application (Häkkinen and Belloni 2011). There is still a lack of a clarified and consensus definition (Pan et al. 2018) to support knowledge development on construction robots. A systems approach is needed for future research to rethink the definition of construction robots, from the "technical" perspective per se toward a dialectical system understanding and communication on construction robots among the wide-ranging stakeholders. Besides, the importance of construction robots has been highly perceived by the stakeholders for future building works in Hong Kong. This emphasizes the research significance to facilitate knowledge management and transfer for construction robots, and to understand how they could be utilized and managed to maximize the contribution to the industry. There is a need for clear guidance, education and standards to serve as the knowledge foundation for future development and application of construction robots, not only for Hong Kong but worldwide.

Theoretical implications of the dialectical system framework

Theoretically, this paper demonstrates and verifies the effectiveness and applicability of the dialectical system framework (Pan and Pan 2018) in comprehending and examining the application of construction robots as innovative building technologies. The framework provides a new perspective for construction robotics studies by applying the dialectical system theory and by integrating the technical systems, stakeholders, and different influencing contexts in the analysis. In particular, the findings reveal the features of the framework in explaining the dialectics of construction robot application, in terms of 1) different stakeholder experiences; 2) multi-dimensional complexity of the task-oriented technical systems; 3) multi-dimensional complexity of contexts; 4) dialectical relationship between technical systems and contexts.

Firstly, the survey results illustrate the experience difference among the key stakeholder groups for construction robots, but do not indicate the perception differentials on construction robots. This finding might be due to the current low level of application and poor understanding of construction robots among stakeholders. Purposeful negotiation among the stakeholders (Sackey et al. 2015) may be needed in the later more mature application stage, when diverging interests and responsibilities (Harty 2008) of stakeholders are more clarified. In this regard, the findings echo previous literature (Zhou et al. 2018) suggesting that stakeholder engagement and role specification are critical for construction robot applications in different contexts, while supplementing that stakeholder engagement patterns may vary between different technology development and application stages.

Secondly, the findings demonstrate the multi-dimensional complexity of task areas for robot applications and highlight the importance of fitness between technology and task, with a 7-dimensional structure of task areas yielded by the EFA. Task diversity in building works could lead to increasing difficulties, complexities, and cost inefficiency (Bock and Linner 2016) for the fit of construction robots to tasks. The findings in this study emphasize the significance of task-technology integration or reconfiguration (Linner et al. 2018) for future robot design and development. The derived dimensions of task areas characterize the complexity of construction robot applications and could provide the basis for future research in this area.

Thirdly, the multi-faced influencing factors from different contexts were perceived to affect the future utilization of construction robots, which is consistent with previous studies on construction innovation (Harty 2008; Whyte and Sexton 2011; Delgado et al. 2019; Pan et al. 2020). In particular, the EFA yielded a 5-dimensional structure of influencing contexts, which consolidates and extends previous research (Pan et al. 2020) to unravel the close coupling of human-related (social) and technology-related (technological) factors, as the socio-technological context, in the future utilization of construction robots. This uncovers the inextricable nature of social and technological factors in the application of construction robots.

Fourthly, the findings reveal that there are strong or moderate interdependencies between the technical systems within complex and dialectical contexts in the application of construction robots, requiring multiple levels of analysis in a systems manner. The economic and socio-technical contexts, as the key considerations by Delgado et al. (2019) for robot adoption, were found to be most strongly correlate with the dimensions of the technical system. Some task areas have different levels of correlations with contexts, which divulge the needs to incorporate different contextual requirements in construction robot design. While previous studies have reported different application areas (Linner et al. 2018; Zhou et al. 2018) and influencing considerations (Delgado et al. 2019; Pan et al. 2020) of construction robots, this research argues for an integrative perspective to manage construction robot development and application considering different tasks and contextual requirements.

The discussion above describes the essential aspects of the dialectical system framework reflecting survey findings and demonstrates the linkage and contribution to previous studies in both construction robot research and the board field of construction innovation. Therefore, the framework should be capable of explaining the utilization mechanisms of both construction robots and other innovative technologies in the building sector, and could provide construction managers and policymakers a systematic understanding of construction robot application to further inform technology strategies and policy initiatives.

The framework theoretically contributes to the understanding of technology application by concerning the dialectics of contexts and stakeholders in the technical systems of construction robot applications. This also explains the slow progress of construction robots in real-world application (Linner et al. 2018). However, there is still ample room for exploration. Examining and refining the theoretical base of technology application focusing on construction robots and other innovative technologies are potential areas for further works. Besides, the implementation of construction robots as new technologies involves organizational changes (Erdogan et al. 2014) that should be well-managed. Future research could also integrate theoretical concepts of organizational change management, such as Kotter's (2012) eight-stage process, to investigate successful applications of construction robots from the change management perspective.

Recommendations for promoting the effective application of construction robots

The findings reveal that although construction robots have promising prospects and good opportunities, they are fraught with uncertainties and dialectics in the building sector in Hong Kong. Insightful recommendations for the future effective application of construction robots are formulated as follows.

The critical role of government

The questionnaire and interview findings highlight the critical role of the government on various fronts, in terms of financial and non-financial support, government procurement and demonstration, policies and standards. The concern of institutional barriers has been raised by early researchers in construction automation and robotics (Mahbub 2008), while the need for government support, including funding and incentive schemes, has significantly been advocated for robots and other innovative technologies (World Economic Forum 2018). As the largest developer, the government should engage more directly and influentially to promote construction robots through adoption and demonstration in public projects or pilot projects. The sharing of knowledge and good practice across the industry could catalyze innovation take-up (Pan and Pan 2018). The government should also actively liaise with different stakeholders across the entire sector to gear up the technology development and knowledge sharing of construction robots, help to clarify stakeholder interests and responsibilities, and to fully leverage technology advantages for the industry betterment.

Robot application for off-site and modular construction

According to the survey results, off-site production/prefabrication is deemed as the most important area for the future utilization of construction robots in Hong Kong. Off-site production has long been a hot spot in the Hong Kong building sector, from traditional precast concrete production (Pan and Pan 2019) to the recently proposed innovative modular integrated construction (Pan and Hon 2018). However, factories are currently all located outside of Hong Kong due to the locally high land and labor costs (Pan and Pan 2019). The advancement of robots could address these issues through enhanced productivity and reduced workforce, and thus enabling to move back the factories to save logistic time and costs as well as reduce transportation waste.

International technology transfer and localized adaptations

The availability of robotic technology is recognized as the most influencing factor of the future utilization of construction robots in Hong Kong, which reveals the current shortage of commercialized products and the immature market. There is a need for promoting international technology transfer to speed up the progress of robots entering the construction industry. Besides, construction companies should collaborate closely with robot developers to work out bespoke solutions to satisfy the local industry needs and lessen the availability concerns. In this respect, technology availability highly correlates with technology compatibility should fit the localized specific contexts. Along with the international technology transfer and localized adaptations, the other highlighted technological issues in the survey could be addressed as well. Availability could also be an important indicator for the assessment of construction robots (Pan et al. 2018) to support decision-making.

Task-technology integrative and iterative design for construction robots within specific contexts

The simple match of the task with technology or traditional task-oriented design of construction robots is insufficient to address the complexities and dialectics of the application of construction robots. There is a need for task-technology integrative and iterative design for construction robots capable of meeting task requirements of those attached more importance and adapting to specified contextual conditions This could also enable the achievement of multi-functional and task-generalizable potentials (Linner et al. 2018) of construction robots. From a systems engineering perspective (NASA 2007), technical systems requirements should be functionally and logically decomposed within contextual conditions to drive for an integrative and iterative design.

Conclusions

This paper has investigated the perspectives of key stakeholders on the future application of construction robots by applying the dialectical system theory. The investigation was carried out through a questionnaire survey and follow-up interviews with wide-ranging industry professionals. A dialectical system framework that incorporates the dialectics of the technical systems, stakeholders, and contexts was adapted as the theoretical underpinning. This dialectical approach is for the first time applied to the field of construction robots.

The findings indicate that construction robots have minimal relevant applications and are poorly understood by the practitioners in Hong Kong, but were perceived important for future buildings in a wide range of task areas, especially in off-site production, cranes and site lifting, and demolitions, involving specific robots (e.g., welding robots for off-site manufacturing, demolition robots) or upgraded robotic equipment (e.g., automatic unmanned cranes, gantry robots). The findings demonstrate the multi-dimensional complexity of task areas and influencing contexts for the future utilization of construction robots for buildings in Hong Kong. The availability of robotic technology was found to be the major concern regarding future real-world applications. Besides, the findings reveal the interdependencies between the technical systems within the dialectical contexts of applying construction robots, and thus further verify the dialectics of the proposed framework.

This paper contributes to the body of knowledge in the field of construction robot and broad technology management by proposing a dialectical system framework to examine construction robot applications, which could provide decision-makers a comprehensive understanding and thus better-informed technology strategies and policy initiatives of construction robots. From a research perspective, the dialectical system framework provides a new theoretical foundation for understanding and examining construction robot applications in terms of the technical systems, stakeholders, and contexts. Although research in the application of construction robots is quickly emerging, a solid theoretical basis is still lacking. Hence, the proposed framework provides a theoretical basis for the field, which could be applied as a basis to study construction robots in general or to analyze specific application cases. It also demonstrates the applicability of use for other innovative technologies. From a practical perspective, the framework provides a structure by which the key components of construction robot application can be considered and strategized in a systems manner. This paper also presents insightful recommendations for promoting the effective application of robots for buildings in terms of leveraging the critical role of government, capitalizing on off-site and modular construction, encouraging international technology transfer and localized adaptation, and driving task-technology integrative and iterative design.

Further research needs are pointed out in the knowledge development of construction robots, more empirical studies to verify and refine the dialectical system framework in elaborating and guiding construction robot applications, and integrating perspectives from organizational change management for successful robot applications. Cross-technology comparisons can also be conducted to generate more insights into the dialectical features of robotic technology applications in the construction industry.

Data Availability Statement

All data, models, and code generated or used during the study appear in the submitted article.

References

Agustí-Juan, I., Müller, F., Hack, N., Wangler, T. and Habert, G. (2017). Potential benefits of digital fabrication for complex structures: Environmental assessment of a robotically fabricated concrete wall. *Journal of Cleaner Production*, 154, 330-340.

Aris, I., AK, M. P. I., Ramli, A.R. and Shamsuddin, S. (2012). Design and development of a programmable painting robot for houses and buildings. *Jurnal Teknologi*, 42(1), 27-48.

Bock T. (2015). The future of construction automation: Technological disruption and the upcoming ubiquity of robotics. *Automation in Construction*, 59, 113-121.

Bock T. and Linner T. (2016). *Construction Robots: Elementary Technologies and Single-Task-Construction Robots*. New York, NY: Cambridge University Press.

Bogue, R. (2018). What are the prospects for robots in the construction industry? *Industrial Robot: An International Journal*, 45(1), 1-6.

Buildings Department. (2019). Buildings Department List of Registered Professionals or Contractors. https://www.bd.gov.hk/en/resources/online-tools/registers-search (accessed 10 February 2019)

Chan, A. P., Darko, A., Ameyaw, E. E., and Owusu-Manu, D. G. (2016). Barriers affecting the adoption of green building technologies. *Journal of Management in Engineering*, 10.1061/(ASCE)ME.1943-5479.0000507.

Chief Executive. (2018). The Chief Executive's 2018 Policy Address: Striving Ahead Rekindling Hope. Retrieved from: https://www.policyaddress.gov.hk/2018/eng (accessed 10 November 2018)

Construction Industry Council (CIC). (2017). Construction Innovation and Technology Application Centre. http://www.cic.hk/eng/main/innotechcentre (accessed 10 November 2018)

Costello, A. B., and Osborne, J. (2005). “Best practices in exploratory factor analysis: Four recommendations for getting the most from your analysis.” *Practical Assessment, Research, and Evaluation*, 10 (7).

Delgado, J. M. D., Oyedele, L., Ajayi, A., Akanbi, L., Akinade, O., Bilal, M., and Owolabi, H. (2019). Robotics and automated systems in construction: Understanding industry-specific challenges for adoption. *Journal of Building Engineering*, 26, 100868.

Development Bureau. (2019). Hong Kong Development Bureau List of Approved Contractors for Public Works. https://www.devb.gov.hk/Contractor.aspx?section=80andlang=1 (accessed 10 February 2019)

Development Bureau. (2018). Construction 2.0 - Time to change. Hong Kong. https://www.hkc2.hk/en (accessed 1 May 2019)

Erdogan, B., Anumba, C. J., Bouchlaghem, D., and Nielsen, Y. (2014). “Collaboration environments for construction: Management of organizational changes.” *Journal of Management in Engineering*, 10.1061/(ASCE)ME.1943-5479.0000231.

Fellows, R. F and Liu, A. M. M. (2015). *Research Methods for Construction*, 4th ed. Oxford: Wiley-Blackwell.

Gammon. (2017). “The rise of robotics Gammon technologies and the changing face of construction.” *The Record*, 1, 12-17.

Ghosh, S. and Jintanapakanont, J. (2004). Identifying and assessing the critical risk factors in an underground rail project in Thailand: a factor analysis approach. *International Journal of Project Management*, 22(8), 633-643.

Giftthaler, M., Sandy, T., Dörfler, K., Brooks, I., Buckingham, M., Rey, G., Kohler, M., Gramazio, F. and Buchli, J. (2017). Mobile robotic fabrication at 1: 1 scale: the in situ fabricator. *Construction Robotics*, 1(1-4), 3-14.

Häkkinen, T., and Belloni, K. (2011). Barriers and drivers for sustainable building. *Building Research and Information*, 39(3), 239-255.

Hair, J. F., Black, W. C., Babin, B. J., and Anderson, R. E. (2010). Multivariate Data Analysis. Essex: Pearson Education.

Harty, C. (2008). Implementing innovation in construction: contexts, relative boundedness and actor-network theory. *Construction Management and Economics*, 26(10), 1029-1041.

Hong Kong Trade Development Council. (2019). Hong Kong Trade Development Council Database of Architectural and Civil Engineering Works at Construction Site. http://service-providers.hktdc.com/manufacturers/Architectural-Civil-Engineering-Works-At-Construction-Site-Service-Providers/en/1352-1 (accessed 10 February 2019).

Hong Kong Special Administration Region (HKSAR) Government. (2017). Construction Workers Registration Ordinance (Cap. 583), Hong Kong e-Legislation, Hong Kong. https://www.elegislation.gov.hk/hk/cap583 (accessed 15 January 2018).

International Organization for Standardization (ISO). (2012). ISO 8373:2012. Robots and robotic devices– Vocabulary.

Izard, J. B., Dubor, A., Hervé, P. E., Cabay, E., Culla, D., Rodriguez, M., and Barrado, M. (2018). On the Improvements of a Cable-Driven Parallel Robot for Achieving Additive Manufacturing for Construction. In: *Cable-Driven Parallel Robots*. Springer, Cham. pp. 353-363.

Lam, P. T., and Fu, F. C. (2019). “Exploratory study on current status of startups in the Hong Kong built environment sector.” *Journal of Management in Engineering*, 10.1061/(ASCE)ME.1943-5479.0000696.

Lee, S., Gil, M., Lee, K., Lee, S., and Han, C. (2007). Design of a ceiling glass installation robot. In: *Proceedings of the 24th International Symposium on Automation and Robotics in Construction* (pp. 247-252). Kochi, India: IAARC.

Li, Y., and Liu, C. (2019). “Applications of multirotor drone technologies in construction management.” *International Journal of Construction Management*, 19(5), 401-412.

Linner, T. (2013). *Automated and Robotic Construction: Integrated Automated Construction Sites.* Doctoral dissertation, Technical University of Munich, https://mediatum.ub.tum.de/doc/1131018/file.pdf (accessed 5 March 2018).

Linner, T., Pan, M., Pan, W., Taghavi, M., Pan, W. and Bock, T. (2018). “Identification of Usage Scenarios for Robotic Exoskeletons in the Context of the Hong Kong Construction Industry.” In *Proceedings of the 35th*

International Symposium on Automation and Robotics in Construction (pp. 40-47). Berlin, Germany: IAARC.

Kotter, J. P. (2012). *Leading change*. Boston, Massachusetts: Harvard Business Review Press.

Mahbub R. (2008). *An Investigation into the Barriers to the Implementation of Automation and Robotics Technologies in the Construction Industry*, Doctoral dissertation, Queensland University of Technology, https://eprints.qut.edu.au/26377 (accessed 5 January 2017).

Nahangi, M., Czerniawski, T., Haas, C. T., Walbridge, S., and West, J. (2015). "Parallel systems and structural frames realignment planning and actuation strategy." *Journal of Computing in Civil Engineering*, 10.1061/(ASCE)CP.1943-5487.0000545.

National Aeronautics and Space Administration (NASA) (2007), NASA Systems Engineering Handbook. Washington, DC: NASA.

Pan, M., Linner, T., Cheng, H. M., Pan, W. and Bock, T. (2018). "A framework of indicators for assessing construction automation and robotics in the sustainability context." *Journal of Cleaner Production*, 182, 82-95.

Pan, M., Linner, T., Cheng, H. M., Pan, W. and Bock, T. (2020). "Influencing factors of the future utilisation of construction robots for buildings: A Hong Kong perspective." *Journal of Building Engineering*, 101220.

Pan, M., and Pan, W. (2019). "Determinants of adoption of robotics in precast concrete production for buildings." *Journal of Management in Engineering*, 10.1061/(ASCE)ME.1943-5479.0000706.

Pan, W., and Ning, Y. (2015). "The dialectics of sustainable building." *Habitat International*, 48, 55-64.

Pan, W., and Hon, C. K. (2018). "Modular integrated construction for high-rise buildings." *Proceedings of The Institute of Civil Engineers – Municipal Engineer*, 1800028.

Pan, W., and Pan, M. (2018). "A dialectical system framework of zero carbon emission building policy for high-rise high-density cities: Perspectives from Hong Kong." *Journal of Cleaner Production*, 205, 1-13.

Real Estate Developers Association. (2019). Real Estate Developers Association of Hong Kong List of Directors and Committee Members. http://www.reda.hk/board (accessed 10 February 2019).

Robotic Industries Association. (2018). Construction Robots-Construction Robots Have Major Disruptive Potential in a Heavily Manual Industry. https://www.robotics.org/service-robots/construction-robots (accessed 3 October 2018).

Sackey, E., Tuuli, M., and Dainty, A. (2014). "Sociotechnical systems approach to BIM implementation in a multidisciplinary construction context." *Journal of Management in Engineering*, 10.1061/(ASCE)ME.1943-5479.0000303.

Saidi, K. S., Bock, T. and Georgoulas, C. (2016). Robotics in construction, In: B. Siciliano and O. Khatib. (Eds.) *Springer Handbook of Robotics* (2nd ed) (pp. 1493-1520). Cham: Springer.

Shen, X., and Lu, M. (2012). "A framework for indoor construction resources tracking by applying wireless sensor networks." Canadian Journal of Civil Engineering, 39(9), 1083-1088.

Slaughter, E. S. (2000). "Implementation of construction innovations." *Building Research and Information*, 28(1), 2-17.

Skibniewski, M. J. (1992). "Current status of construction automation and robotics in the United States of America." In: *The 9th International Symposium on Automation and Robotics in Construction* (pp. 17-26). Tokyo, Japan.

Taghavi, M., Heredia, H., Iturralde, K., Halvorsen, H. and Bock, T. (2018). "Development of a Modular End Effector for the installation of Curtain Walls with cable-robots." *Journal of Facade Design and Engineering*, 6(2), 1-8.

Wang, J., Sun, W., Shou, W., Wang, X., Wu, C., Chong, H.Y., Liu, Y. and Sun, C. (2015). Integrating BIM and LiDAR for real-time construction quality control. *Journal of Intelligent and Robotic Systems*, 79(3-4), 417-432.

Whittaker, W. L. (1986). "Construction robotics: a perspective." In: *CAD and Robotics in Architecture and Construction, Proceedings of the Joint International Conference at Marseilles* (pp. 105-112). Paris, France: Hermes Publishing.

Widén, K., Olander, S., and Atkin, B. (2013). "Links between successful innovation diffusion and stakeholder engagement." *Journal of Management in Engineering*, 10.1061/(ASCE)ME.1943-5479.0000214.

Whyte, J., and Sexton, M. (2011). "Motivations for innovation in the built environment: new directions for research." *Building Research and Information*, 39(5), 473-482.

World Economic Forum. (2018). *Future Scenarios and Implications for the Industry.* http://www3.weforum.org/docs/Future_Scenarios_Implications _Industry_report_2018.pdf (accessed 1 March 2019).

Wu, W., and Issa, R. R. (2014). "BIM execution planning in green building projects: LEED as a use case." *Journal of Management in Engineering*, 10.1061/(ASCE)ME.1943-5479.0000314.

Yang, Y., Pan, M., and Pan, W. (2019). "'Co-evolution through interaction' of innovative building technologies: The case of modular integrated construction and robotics." *Automation in Construction*, 107, 102932.

Yeon, J., Rew, Y., Choi, K., and Kang, J. (2020). "Environmental Effects of Accelerated Pavement Repair Using 3D Printing: Life Cycle Assessment Approach." *Journal of Management in Engineering*, 10.1061/(ASCE)ME.1943-5479.0000752.

Zhou, Z., Irizarry, J. and Lu, Y. (2018). "A multi-dimensional framework for unmanned aerial system applications in construction project management." *Journal of Management in Engineering*, 10.1061/(ASCE)ME.1943-5479.0000597.

Zigurs, I., and Buckland, B. K. (1998). "A theory of task/technology fit and group support systems effectiveness." *MIS quarterly*, 22(3).

Table 1: A review of relevant definitions of construction robots

Authors	**Definition**
Whittaker (1986)	A construction robot is a robot that constructs, meaning builds, and yet such robots do a lot more; they exhibit flexibility in the roles they play and the equipment they use, and they perform tasks of a complexity that previously required human control.
Skibniewski (1992)	Construction automation is the engineering of any construction process using teleoperated, numerically controlled, semi-autonomous, or autonomous equipment, while construction robotics is the advanced construction equipment with the capability related to teleoperation, acquisition and analysis of sensory data, numerically controlled, or autonomous tasks.
Lee et al. (2007)	Construction robots are field robots that execute orders while operating in a dynamic environment where structures, operators, and equipment are constantly changing.
Mahbub (2008)	Construction automation and robotics is the use of self-control mechanical and electronic machinery with intelligent control mechanisms to conduct construction tasks and operations automatically.
Aris et al. (2012)	Construction robots are ingenious machines that use intelligent control but vary in sophistication, including advanced automation and remote-control devices used on the construction site and prefabrication shop.
ISO (2012)	A robot is an actuated mechanism programmable in two or more axes with a degree of autonomy, moving within its environment, to perform intended tasks.
Linner (2013)	Single task construction robots are systems that support workers in executing one specific construction process or task (e.g. digging, concrete levelling, concrete smoothening, and painting) or by completely taking over the physical activity of human worker necessary to perform this one process or task.
Nahangi et al. (2015)	Construction robots are used for repetitive tasks such as module assembly, and operations in harsh conditions such as tunnel inspection.
Saidi et al. (2016)	Construction robotics is an advanced form of mechanization (automation) in which an endeavor is made to automate some industrially important operation and thereby reduce the cost of this operation by either removing a human operator from the control loop, or enhance operational efficiency through machine control systems.
Robotic Industries Association (2018)	Construction robots are professional service robots currently used in the construction of new buildings.

Table 2: Primary organizational affiliations (stakeholder groups) of interviewees

Primary area of practice	**Number**
Contractors (main and sub)	7
Developers, Clients and Investors	2
Professional advisors	3
Government and its agencies	3
Manufacturers and Suppliers	2
Universities and professional bodies	3

Table 3: Results on the importance of task areas for future construction robots

Task areas	Mean (SD)	RII	R	ANOVA Sig.[a]	Factor loading	Cronbach's α
Groundworks						0.785
T1: Geotechnical, foundation and pilling works	3.45 (1.10)	0.69	11	Nil[b]	0.674	
T2: Ground investigation, site measuring, and monitoring	3.48 (1.06)	0.7	9	0.10	0.747	
T3: Civil works (e.g. slope, ground water drainage)	3.22 (1.03)	0.65	17	0.16	0.653	
Site operation						0.737
T4: *Site operation* - Crane and site lifting operation	3.66 (1.04)	0.73	3	**0.03**	0.674	
T5: *Site operation* - Site logistics	3.46 (1.06)	0.69	10	0.75	0.858	
T6: *Site operation* - Scaffolding	3.12 (1.20)	0.62	18	0.53	Nil[c]	
Main structure construction						0.888
T7: *Main structure construction* - Reinforcement bar fixing and positioning	3.52 (1.06)	0.7	8	0.63	0.834	
T8: *Main structure construction* - Structural steel work	3.58 (1.04)	0.72	5	0.85	0.830	
T9: *Main structure construction* - Formwork	3.40 (1.05)	0.68	14	0.23	0.654	
T10: *Main structure construction* - Concreting (e.g. concrete paving and compaction)	3.45 (1.08)	0.69	11	0.32	0.577	
T11: *Main structure construction* - Facade installation (e.g. curtain wall installation)	3.56 (1.03)	0.71	6	0.85	0.523	
Building services and finishing works						0.846
T12: Building services works (e.g. Heating, ventilation, and air conditioning, lift installation)	3.09 (1.03)	0.62	20	0.46	0.529	
T13: *Finishing works* - General interior finishing works	3.02 (1.11)	0.6	21	0.99	0.894	
T14: *Finishing works* - General exterior finishing works	3.35 (1.06)	0.67	16	0.96	0.823	
T15: *Finishing works* - Landscaping (e.g., greening)	2.84 (1.07)	0.57	22	0.67	0.537	
T16: General assistance (e.g., exoskeletons for power augmentation)	3.38 (1.04)	0.68	15	0.47	Nil[c]	
T17: Metal work (e.g. steel welding)	3.53 (0.98)	0.71	7	0.60	Nil[c]	
Maintenance and renovation						0.800
T18: Building maintenance (e.g., facade inspection)	3.44 (1.11)	0.69	13	Nil[b]	0.811	
T19: Building renovation and fitting-out	3.05 (1.06)	0.61	19	**0.03**	0.680	
Factory-based production						0.713
T20: Off-site production/prefabrication	4.07 (0.87)	0.81	1	0.07	0.781	
T21: Automated/robotic on-site factories	3.78 (1.04)	0.76	2	Nil[b]	0.773	
Demolition works						—
T22: Demolition	3.62 (1.16)	0.72	4	0.92	0.850	

Note: Calculations are based on a 5-point Likert scale consisting of 'Not important at all' as 1, 'Slightly important' as 2, 'Somewhat important' as 3, 'Important' as 4 and 'Very important' as 5.

[a] $p < 0.05$: at 0.05 level respondents' opinions are different across the different groups.

[b]: Assumption of homogeneity of variance was violated.

[c]: Task areas deleted in EFA due to low communality or loading.

Table 4: Results on the influencing contexts of future development and use of construction robots for buildings in Hong Kong

Contexts and influencing factors	Mean (SD)	ANOVA Sig.[a]	RII	R	Factor loading	Cronbach's α
Economic context						0.820
IF1: Economic environment	3.86 (0.96)	0.53	0.771	13	0.675	
IF2: Construction productivity	4.12 (0.82)	0.09	0.824	3	0.685	
IF3: Construction cost	4.13 (0.88)	0.51	0.825	2	0.734	
IF4: Initial investment cost and economic performance associated with robots	4.11 (0.84)	0.13	0.823	4	0.658	
Environmental context						0.871
IF5: Demand for environmentally friendly buildings	3.42 (1.05)	0.58	0.684	20	0.771	
IF6: Land resource for building construction	3.34 (0.98)	0.30	0.667	22	0.674	
IF7: Climate change	3.05 (1.09)	0.57	0.611	25	0.827	
IF8: Awareness of environmental impacts of construction activities	3.40 (0.97)	0.47	0.681	21	0.765	
IF9: Charging for Construction Waste Disposal	3.23 (1.11)	0.06	0.647	23	0.636	
IF10: Size and number of households	3.07 (1.06)	0.24	0.613	24	0.656	
Industrial context						0.815
IF11: Fragmentation and collaboration of the industry	3.60 (0.87)	0.91	0.719	17	0.601	
IF12: Unstructured, dynamic and unique site environment	3.55 (0.90)	0.85	0.711	18	0.710	
IF13: The scale of prefabrication	3.96 (0.80)	0.05	0.792	9	0.578	
IF14: Globalization in construction	3.54 (0.92)	0.26	0.708	19	Nil[b]	
IF15: Building typology	3.72 (0.84)	0.42	0.745	14	0.666	
IF16: Culture of innovation in the industry	3.69 (0.92)	0.64	0.737	15	0.708	
Political context						0.756
IF17: Government labor policy	3.90 (0.87)	0.05	0.781	10	0.709	
IF18: Government policy on foreign workers	3.63 (1.01)	0.64	0.727	16	0.599	
IF19: Governmental support on robotics applications in construction	4.09 (0.93)	0.20	0.818	5	0.566	
Socio-technological context						0.865
IF20: Occupational safety and health performance	3.88 (0.92)	0.70	0.776	12	0.642	
IF21: Work structure and organization	3.89 (0.82)	0.70	0.778	11	0.541	
IF22: The uptake of information and communication technology	3.97 (0.83)	0.43	0.794	8	0.727	
IF23: Technological difficulty to provide robotics performance features	4.08 (0.88)	0.17	0.817	6	0.764	
IF24: Ease of use of robots	4.07 (0.92)	0.05	0.814	7	0.754	
IF25: Availability of robotic technology	4.19 (0.84)	0.10	0.837	1	0.674	

Note: Calculations based on a 5-point Likert scale consisting of 'Not influential at all' as 1, 'Slightly influential' as 2, 'Somewhat influential' as 3, 'Influential' as 4 and 'Very influential' as 5.

[a] $p < 0.05$: at 0.05 level respondents' opinions are different across the different groups.

[b]: Influencing factor deleted in EFA due to low communality.

Table 5: Correlations between the summated scales of technical systems dimensions and the context dimensions

Context dimensions *Technical system dimensions*	Economic context	Environmental context	Industrial context	Political context	Socio-technological context
Groundworks	**.426****	**.405****	**.488****	.392**	**.439****
Site operation	.395**	.321**	.338**	.369**	**.439****
Main structure construction	**.467****	**.457****	**.463****	.363**	.372**
Building services and finishing works	.386**	**.432****	**.452****	.290**	.319**
Maintenance and renovation	.328**	.321**	.378**	.341**	.370**
Factory-based production	**.439****	.237**	.385**	.352**	**.441****
Demolition works	.339**	.375**	.254**	.337**	**.411****

** Correlation is significant at the 0.01 level (2-tailed).