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Author statement

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Influencing factors of the future utilisation of construction robots for buildings: A Hong Kong perspective

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Abstract

Construction robots are expected to have disruptive impacts on the building industry, but there is still a lack of utilisation. While significant attention has been paid to technical advancement, little has been done to comprehensively understand the broader societal issues associated with the use of this technology. This paper aims to provide a holistic exploration of the influencing factors of the future utilisation of construction robots in a systems manner, analyse the interactions among these factors and identify the key ones that are most influential in shaping the technological transformation. A modified fuzzy decision-making trial and evaluation laboratory (DEMATEL) method is developed and applied. Hong Kong was selected as the desirable case for the study due to its vibrant yet challenging built environments. Factors were first systematically identified and synthesised before being empirically verified, evaluated and analysed through the modified fuzzy DEMATEL. The results demonstrate the multi-faceted and complexly interrelated factors influencing the utilisation of construction robots. Eleven influencing factors were determined as critical for shaping the future trajectory of robotic applications, among which “construction cost”, “governmental support” and “the scale of prefabrication” are the most influential ones. The findings indicate that more interdisciplinary efforts and broader non-technical discussions are needed to achieve the successful transition of the industry towards robotic construction. The findings further reveal the driving forces of environmental pressures behind the future utilisation of construction robots. Detailed utilisation scenarios which fit to the evolution of the whole society are recommended for future research.

Keywords: Influencing factors; utilisation; construction robot; fuzzy DEMATEL; Hong Kong.

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1. Introduction

The building and construction industry is increasingly facing grave challenges on a worldwide level such as stagnant productivity growth, cost escalation, an ageing workforce and skilled labour shortages [1]. Conventional construction methods have reached their limits to meet the growing need for enhancement in productivity, quality, safety and sustainability [2]. The application of robots has been advanced as one of the most promising solutions to reform the industry [3]. However, despite years of research and a growing number of startups and spin-offs, the real-world uptake of construction robots remains limited [4, 5], and the reasons behind this are not entirely understood.

This paper aims to provide a holistic exploration of influencing factors of the future utilisation of construction robots in a systems manner, analyse the interactions among factors and identify the key ones to shape the technological transformation. The ultimate goal is to guide future research and technology development efforts towards being more target-orientated. The exploration of factors was carried out in a multi-dimensional and multi-level manner. A modified fuzzy decision-making trial and evaluation laboratory (DEMATEL) method was developed and applied for a causal effect analysis. While construction automation and robotics cover a broad spectrum of technologies [2], this study narrows the focus to robots for buildings, which are regarded as machines or devices that are programmable, mechanically actuated and have a degree of autonomy, enabling them to perform construction tasks which are normally ascribed to humans. Hong Kong is selected as a desirable case for study. Its building and construction industry has a favourable environment for utilising advanced construction technologies like construction robots. However, few practical attempts in this area have been made thus far [6, 7]. Hong Kong could enable a comprehensive exploration of plausible factors, direct or indirect, that may influence the use of construction robots where the industry is experiencing the most fundamental problems that robots aim to solve. Therefore, it could serve as a universal reference point to understand the essentials to the real-world utilisation of construction robots towards various pressures and challenges.

In the remainder of the paper, the literature review is first presented, followed by the methodology including the systems framework and developed a modified fuzzy DEMATEL method. Then, a holistic review and a systematic analysis based on the systems framework follows, which aims to identify and synthesise the influencing factors. The paper then applies the modified fuzzy DEMATEL method on the identified factors via a survey to evaluate the degree of importance of the individual factors and demonstrate their interrelationships. After discussing the main findings, the paper draws its conclusions and provides recommendations for future research.

2. Construction robots utilisation: evolution, challenge and research

Construction robotics was first discussed in the 1970s, which has triggered a plethora of research development efforts since the initial attempts in the 1980s [8]. To speed up the breakthrough of construction robots, technical studies have increased substantially with compelling technological advancements and new capabilities [8, 9]. Consequently, a number of robotic technologies for on-site building construction have been developed, ranging from single-task robots (e.g. mobile and/or aerial robots, robots for facade installation) to integrated robotic sites, providing evidence for the capability of robotics to assist construction tasks in a more efficient, accurate and safe manner [9]. Cross-sectional technologies such as building information modelling (BIM), distributed sensing systems, intelligent human-machine-interfaces and machine learning applications recently gained momentum in research on construction robotics and hold the potential to serve as interconnecting information backbones for construction robot applications [10]. However, the real-world utilisation of construction robots is still limited [4, 5].

Some previous attempts have been made to interpret the slow adoption and implementation of construction robots. For example, Warszawski and Navon [11] identified four fundamental reasons for the minimal success of robotic adoption in building construction, namely, insufficient development, unsuitable building design, inadequate economic justification and managerial barriers. Mahbub [12] analysed and ranked the obstacles preventing the infiltration of construction automation and robotics in Japan, Australia and Malaysia with differing levels of usage. Quezada, et al. [10] indicated the inward and outward forces pushing the construction industry towards automation and robotic use and further highlighted the consequences on skill requirements and job profiles. Despite the contributions of these studies, concerns are primarily on the factors associated with technology and process, and the coupling influence of factors on technological use is poorly investigated. Construction robots and their evolution as radical innovations to the industry should be embedded in the social movements, which are not only technically and economically formed, but socially shaped by interactions among various stakeholders [13]. Hence, to explore how construction robots can successfully gain in utilisation and unlock their potential for large-scale applications, a broader analytical perspective that considers both technical and non-technical issues and their interplay is required.

3. A systems framework for influencing factors of the utilisation of construction robots

Systems approaches have been proposed to understand technology evolution and transition as complex systems that involve the whole set of stakeholders, processes, products, technologies, business, policies, culture and skill development. These systems have been described using terms such as "socio-technical" [13], "ecological" [14], or "dialectical" [15], foundational to which is the emphasis on the complexity, dynamics and multi-dimensional nature of systems' elements and their interactions.

Studies on construction robots have concentrated on "technical" aspects, while insufficient research has comprehensively explored the "non-technical" factors and interactions among them to influence the real-world utilisation. Drawing on the systems theory, this study argues for a systems approach to examine the utilisation of construction robots as complex systems, which integrates the multi-level perspective (MLP) [13] and the PESTLE (political, economic, socio-cultural, technological, legal, environmental) model [16]. The MLP has been widely applied to explain and analyse the technological transitions as interactive processes of change, which highlights the co-evolution and multi-dimensional interplay at three conceptual levels: landscape, regimes and niches [13]. The landscape level includes external factors that exert influence on regimes and niches, the regime level refers to the rules embedded in social networks and technological artefacts to fulfil a certain societal function such as building supply, and niches, which are radical innovations that deviate from the current regime [13]. The PESTLE is a useful analytical tool for examining factors in a multi-dimensional way [16], which could underpin a systematic exploration of factors in niches, regimes and landscape. The dimension of industry was identified as an additional area to cover the factors reflecting the characteristics of the industry, which is widely acknowledged to influence construction innovation [17]. The integrated systems framework was illustrated in Fig. 1. The three levels in the framework present that, firstly, construction robots as niche-innovations create the internal momentum for breakthrough; secondly, the landscape creates pressures on the regime; and thirdly, challenges in the regime (destabilisation) create opportunities for niche-innovations to entry and generate transitions. For each level, the potential changes are influenced by factors from different dimensions.

Therefore, the framework goes beyond studies of individual technologies, supporting a multi-dimensional, multi-level exploration of factors influencing the successful transition to construction robots.

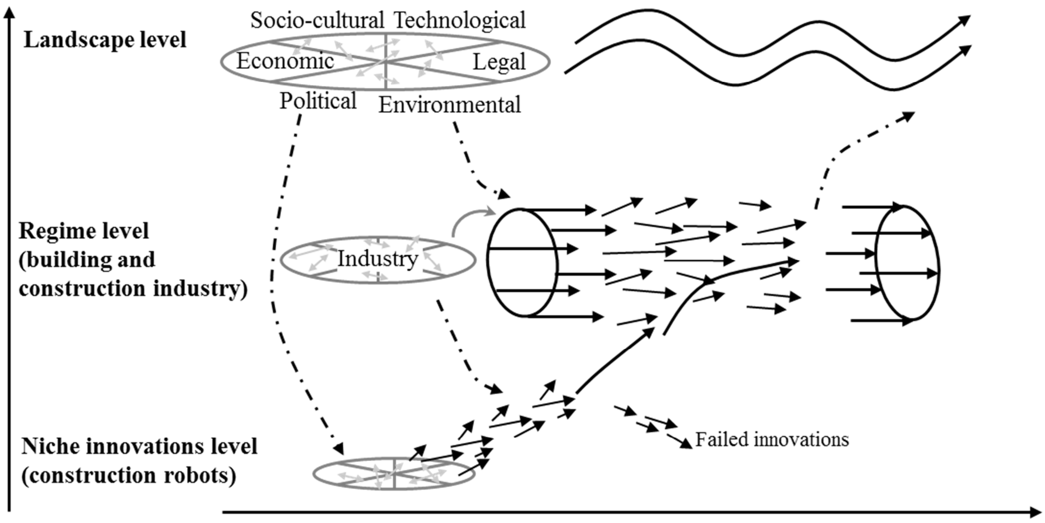

Fig. 1. A systems framework for a multi-dimensional, multi-level exploration of influencing factors of the utilisation of construction robots (based on [13] and [16])

4. The exploration of influencing factors

The exploration of influencing factors was carried out within the context of Hong Kong while referring to the broader worldwide knowledge base. Over the years, construction companies in Hong Kong have developed their expertise and gained a reputation for quality performance in such a large and fast-growing market [18]. However, considerable challenges are emerging as the city is not only suffering from a rapidly ageing population but also a deteriorating building stock, and the industry is struggling to satisfy the ever-increasing demand for building construction [19]. Under the condition of land scarcity in Hong Kong, the increasing number of skyscrapers being constructed in increasingly dense areas has become a trend, thus triggering the technical challenges and safety issues. All these issues create a favourable environment for utilising advanced construction technologies like construction robots.

Based on the theoretical framework, 65 influencing factors (see in Appendix A) were initially identified from the literature, brainstorming and expert interviews. Although some of the reviewed studies focus on other types of construction innovations, the factors influencing their real-world adoption should share some common traits with the implementation of construction robots. The initially identified factors were combined and synthesised. The legal factors were integrated into the political area, considering their pertinence to political issues and the level of enforcement. Finally, 25 factors from three levels are summarised in the economic, environmental, industry, political, socio-cultural and technological areas (Table 1).

Table 1 Identified influencing factors

Influence areas	Influence factors [L/R/N]
Economic (4 Factors)	F1: Economic environment [L]
	F2: Productivity (e.g. labour, time) [R]
	F3: Construction cost (e.g. material, labour) [R]
	F4: Initial investment cost and economic performance associated with robots [N]
Environmental (4 Factors)	F5: Demand for environmentally friendly buildings [L/R]
	F6: Land resource for building construction [L]
	F7: Climate change [L]
	F8: Awareness of environmental impacts of construction activities (e.g. construction waste, air quality, energy consumption) [R]
Industry (5 Factors)	F9: Fragmentation and collaboration of the industry [R]
	F10: Unstructured, dynamic and unique site environment [R]
	F11: The scale of prefabrication [R]
	F12: Globalisation in construction [R]
	F13: Building typology (e.g. height, diversity and architectural freedom) [R]
Political (4 Factors)	F14: Government labour policy (e.g. occupational safety and health, working hours) [L]
	F15: Charging for Construction Waste Disposal [R]
	F16: Government policy on foreign workers [L/R]
	F17: Governmental support on robotics applications in construction (e.g. financial, guidance, public procurement, legal issues for robots) [R/N]
Socio-cultural (4 Factors)	F18: Size and number of households [L]
	F19: Culture of innovation in the industry [R/N]
	F20: Occupational safety & health performance [R]
	F21: Work structure and organisation (e.g. age structure of the workforce, shortage of skilled labour, education and training) [R]
Technological (4 Factors)	F22: The uptake of information and communication technology (e.g. BIM, IoT) [R]
	F23: Technological difficulty to provide robotics performance features (e.g.

	robustness, flexibility, advanced sensing, interoperability) at reasonable cost levels [N]
	F24*:* Ease of use of robots (e.g. usability, size, weight, power supply) [N]
	F25*:* Availability of construction robotics [L/N]

L/R/N: L – landscape level; R – regime level; N – niche innovations level
References: World Economic Forum [1]; Saidi et al. [4]; Bogue [3]; Pan et al. [5]; Wong et al. [6]; Bock and Linner [9]; Quezada et al.[10]; Warszawski and Navon [11]; Mahbub [12]; Kangari and Halpin [20]; Lim et al. [21]; Skibniewski and Zavadskas [22]; Agustí-Juan et al. [26]; Blayse and Manley [27].

4.1. Economic factors

The economic environment is a critical concern at the landscape level to influence the real-world application of construction robots. Evidence has been witnessed in Japan that construction activities have plunged after the burst of the bubble economy in the late 1990s, limiting the development of construction automation and robotics [12]. Considering the regime requirements, the need to improve construction productivity is a significant driver for adopting robotics [1, 6, 20-22], but the tight project timeframes could also inhibit the implementation of new technologies like robots, which require change arrangement and more rigorous planning [12]. Another relevant factor is the construction cost [1, 10, 21]. Hong Kong's construction industry is suffering from high labour costs, and industry players are generally interested in any machinery or technology that could save labour [6]. Construction materials in Hong Kong are primarily imported with escalation trends which may facilitate the adoption of robots to save on material and reduce waste [23]. An influential economic factor concerning the niche level is the high capital costs and lack of long-term economic justification of construction robots [8, 24], which can affect the interest of construction companies on investment.

4.2. Environmental factors

The adverse impacts of building and construction on the environment and public are critical in terms of carbon emissions, wastage demolition, noise pollution and disturbance to the surrounding areas [5]. The greening of the building sector and increasing awareness of construction activities calls for innovative approaches to construction, offering an excellent opportunity for adopting robots [5]. Hong Kong, as a compact city, is also facing significant challenges in managing the impact of building construction works on the environment and public. Hong Kong has for a long time been plagued by land shortages [6], which could require the use of robots to construct more high-rise buildings and minimise the land requirement for C&D (construction and demolition) waste disposal [5]. Despite regulatory control, construction noise remains a tricky problem in Hong Kong [25]. Additionally, with rising temperatures and severe weather conditions associated with climate change, there may be a severe challenge for future construction works, as a jumping-off point for utilising automation and robotics [10, 26].

4.3. Industry factors

The construction industry characteristics derive many influencing factors at the regime level. Firstly, the fragmented nature of the industry often makes it reluctant to accept change and innovations [27]. The multi-point responsibility leads to difficulties in robotic applications, while the increase of internal collaborations and collaboration with other advanced industries could enable knowledge-sharing and benchmarking in robotic technologies, driving the industry to adopt construction robots [1, 6, 22]. Secondly, the unstructured and dynamic site environment results in difficulties in the control of construction robots, and the uniqueness of specific sites requires case-by-case consideration of using robots, creating barriers of utilisation [6, 11, 12]. Thirdly, the large-scale industrialisation and prefabrication enable a well-organised and standardised on-site environment, where robots can be better integrated to conduct assembly works [4, 9, 10]. However, the large-scale of prefabrication may limit the economic benefits to use robots on-site [28]. Fourthly, the globalisation of the construction industry is deemed as a major influence for the uptake of advanced construction technologies [9, 10]. To gain a competitive edge in the overseas market, robotics could be a valuable investment. Local companies can also efficiently learn up-to-date technologies through partnering arrangements with foreign companies. Lastly, Hong Kong is characterised by high-rise, high-density buildings, and the increasing height of the buildings can be a driver to use robots in the future to avoid aloft work and enable urban mining [10, 21]. Diversity and increasing architectural freedom is deemed as a barrier but also a force driving the industry towards the use of robotics.

4.4. Political and legal factors

Government labour policy is responsible for governing workplace safety and health, stipulating standard working hours and wages. The changing labour policy could facilitate or inhibit the utilisation of robots concerning improved safety, health and productivity performance. Legislative requirements of construction activities in terms of any forms of pollution, waste disposal or consideration of neighbourhood environments could be triggers to use robotic construction [5, 12]. Government policy on foreign workers can influence the implementation of robots in areas such as employment of cheap foreign workers, introducing senior talents [12]. Strong policies and incentive schemes are often effective in promoting the adoption of innovative technologies in the construction industry [1, 6]. Governmental financial and non-financial supports could accelerate the research and development (R&D) efforts and applications of construction robots. The government also has an immense impact on building construction through its role as the client, and can foster the application of robots in the public procurement [1].

4.5. Socio-cultural factors

Societally speaking, the number of domestic households in many places is projected to increase with smaller household size [10], which could change the demand of accommodation types and drive the adoption of robotic-assisted construction. However, the construction industry has been lagging in the new frontiers of technological development [27]. The lack of innovation culture pertinent to the reluctance of changes is a significant inhibitor to acquiring innovative technologies like robots [10, 22] or other new technologies [30]. Another socio-cultural concern is the need for reducing safety and health issues of human workers on the construction sites, which is highlighted as a major driver to use more automation and robotics [1, 6, 20, 21]. Besides, the ever-increasing demand for a workforce, accompanied by skill mismatches and the ageing labour force, poses significant risks to the fulfilment of a productive industry in Hong Kong [6, 7]. The shortage of labour results in increased salaries, which also contributes to the cost escalation of the construction activities [23]. Those challenges in the work structure and organisation provide the golden opportunities for construction robots. Meanwhile, education and training is quite influential to the use of robotics by enhancing the robotic knowledge and competence of the younger generation and existing workers [10, 12, 22].

4.6. Technological factors

The industry-wide uptake of information and communication technology (ICT) such as BIM and Internet of Things (IoT) provides the foundation for automation and robotic applications [10, 28]. Another important consideration is the technological difficulty in providing robotics performance features [9, 11, 12, 20]. Construction robots should be robust, flexible, mobile and versatile due to the unpredictable and hazardous nature of construction sites. The current state of technological development is still insufficient, which creates difficulties and risks when using robots. Future robots should be smarter and better fit to the construction works, supported by the advancements in sensors, laser scanning and artificial intelligence [10]. Besides, ease of use is a key influencer to making the robots more acceptable. The incompatibility, bulkiness, heavy and high-power features of many construction robots that reduce their usability are recognised as constraints for their application [9, 11]. The improvement of usability of construction robots is a critical challenge for future adoption in terms of better understanding of the technology, easier human-robot interface/interaction and control modes, flexible movement and accurate analysis of the complicated surrounding environment [2, 3, 12]. In general, construction companies are more likely to be late followers of innovations. Robotic technologies are still quite new and they are often unavailable locally and difficult to acquire, which is often in and of itself a critical issue for their future utilisation [12].

5. Research methods

The research is carried out in three main stages (see Fig. 2) to analyse and identify the key influencing factors of the future utilisation of construction robots for buildings, based on a modified fuzzy DEMATEL method.

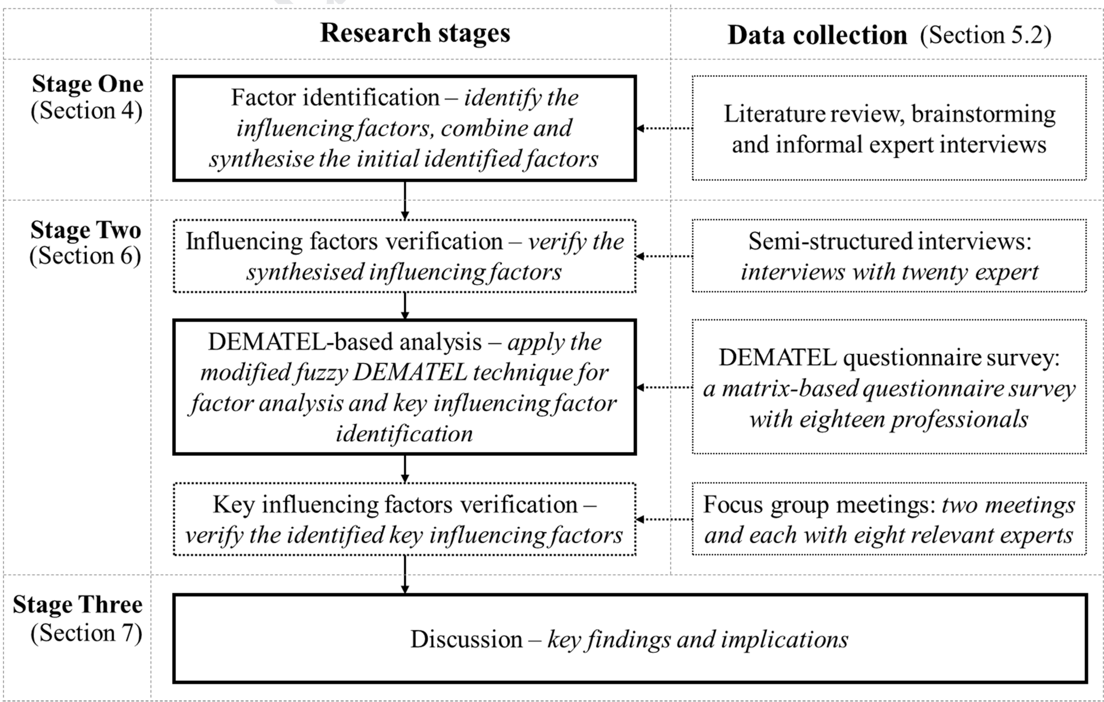

Fig. 2. Research process

- *Stage one* is the factor identification. The influencing factors were first identified through a holistic literature review, brainstorming and informal expert interviews, drawing on the multi-dimensional, multi-level theoretical framework from a systems perspective. The initially identified factors were combined and synthesised.
- *Stage two* is mainly DEMATEL-based analysis. Semi-Structured expert interviews were first conducted to provide triangulated verification for the identified influencing factors in stage one. Then, a modified fuzzy DEMATEL method was applied to analyse the importance of factors and causal relationships with data collected from relevant professionals and, thereby, the factorial relationships and key influencing factors can be determined. Results were then further discussed and verified through focus group meetings, and key influencing factors were finalised.
- *Stage three* is the discussion: key findings are discussed, and implications are explored regarding how the successful shift of construction techniques towards robotics might be achieved.

5.1. A modified fuzzy DEMATEL method

The DEMATEL method was developed in the 1970s by The Battelle Memorial Institute of Geneva to address complicated and correlative problems [31]. It collates related variables in the decision-making or problems into a structural model onto which the importance of the variables can be identified, and causal relationships visualised [32]. Specifically, it is based on digraphs and uses a causal diagram to depict the contextual relationships and the importance of influence among a set of variables or factors, which are also regarded as elements of the studied system [32]. Data is collected from experts, who are asked to assess the pair-wise influence relations of factors in terms of direction and influence within a Likert-type scale. The DEMATEL method, in combination with other techniques, has been widely used to study complicated phenomena and to solve decision-making problems in different fields such as performance assessment [33], strategy selection [34] and critical factors identification [35, 36]. Since the diversified factors might influence the future use of construction robots, it is crucial to identify the key ones and explore how they are interrelated to gain a deep understanding of the whole picture. The DEMATEL method, therefore, fits the purpose of this study and provides the advantages of a systematic approach. Although there are other approaches, such as cross impact analysis [37], applied as standard ways to identify the key influencing factors, most of them only consider the direct impacts of a factor for causal relationship analysis but DEMATEL considers both direct and indirect impacts to provide a more reliable identification of the key influencing factors.

Although the Original DEMATEL is a powerful tool to identify the influence relationships within the systems [32], it is based on crisp values in developing the structural model and thus highly dependent on experts' judgements. However, the judgements are often subjective and expressed in ambiguous lingual expressions based on their experiences and expertise. The fuzzy set theory [38] has been integrated into the DEMATEL in many studies to tackle the ambiguities and unclear issues of human judgement. Fuzzy numbers can describe linguistic terms. Specifically, the triangular fuzzy numbers are commonly used for representing linguistic terms by fuzzy numbers and adopted by previous studies regarding fuzzy DEMATEL method (e.g. [33]). A fuzzy set $\tilde{A}$ is a subset of X (universe of discourse), which is characterised by a membership function $\mu_{\tilde{A}}(x)$. The function value of $\mu_{\tilde{A}}(x)$ is called the membership values of x, representing the degree of truth that x belongs to the fuzzy set $\tilde{A}$. If $\tilde{A}$ is a triangular fuzzy set, it can be defined as a triplet (l,m,r), where $l < m < r$. Then, the membership function $\mu_{\tilde{A}}(x)$ is defined as:

$$\mu_{\tilde{A}}(x)=\begin{cases} 0, & x<l \text{ or } x\geq r \\ (x-l)/(m-l), & l\leq x<m \\ (r-x)/(r-m), & m\leq x<r \end{cases} \tag{1}$$

Furthermore, the DEMATEL or fuzzy DEMATEL method uses a simple averaging technique to combine the judgement results from different professionals. However, people have different judgment criteria, and some may tend to give high scores while some may provide scores that are more differential. Therefore, the same evaluation score may represent different judgements across professionals, and it might not entirely reflect the combined results through averaging. Thus, this study proposes to extend the fuzzy DEMATEL method [33] with a double normalisation operation on the individual matrices to ascertain the reliability of the combined judgement of professionals. The main steps in the modified fuzzy DEMATEL for this study are as follows (also see definition of key notations in Appendix B).

Step 1: Transferring collected data into positive triangular fuzzy numbers. Given the n factors F={F1, F2,…,Fn}, K professionals are asked to evaluate the pair-wise influence with a 4-point scale from [0, 1, 2, 3], representing the linguistic terms [No influence, Low influence, Medium influence, High influence]. For each professional, an n x n initial influence matrix can be generated as $X_k=[x_{ij}^k]_{n\times n}$, where k is the number of professionals with

$1 \le k \le K$. The collected influence score x_{ij}^k represents the judgement of the influence of factor *i* on factor *j*. The fuzzy logic is then introduced to deal with the ambiguities of x_{ij}^k. The evaluation data in the matrices from the individual professional can be transferred into triangular fuzzy numbers. According to Chen and Hwang [39], x_{ij}^k is transferred and expressed in positive triangular fuzzy numbers $\tilde{a}_{ij}^k = \left(l_{ij}^k, m_{ij}^k, r_{ij}^k\right)$ based on Table 2.

Table 2 The fuzzy linguistic scale.

Linguistic terms	Influence score	Corresponding triangular fuzzy numbers
No influence	0	(0, 0, 1/3)
Low influence	1	(0, 1/3, 2/3)
Medium influence	2	(1/3, 2/3, 1)
High influence	3	(2/3, 1, 1)

Step 2: Defuzzificating fuzzy numbers to crisp scores. The defuzzification step transfers the fuzzy numbers of $\tilde{a}_{ij}^k = \left(l_{ij}^k, m_{ij}^k, r_{ij}^k\right)$ back to the crisp scores $\tilde{a}_{ij}^k$, which is performed as follows by Converting Fuzzy data into Crisp Scores algorithm [40], a highly recommended defuzzification method [33].

First, the fuzzy numbers of $\tilde{a}_{ij}^k$ are normalised based on results from all professionals.

$$l'^k_{ij} = \left(l_{ij}^k - \min_{1\le k\le K} l_{ij}^k\right) \Big/ \left(\max_{1\le k\le K} r_{ij}^k - \min_{1\le k\le K} l_{ij}^k\right) \quad (2)$$

$$m'^k_{ij} = \left(m_{ij}^k - \min_{1\le k\le K} l_{ij}^k\right) \Big/ \left(\max_{1\le k\le K} r_{ij}^k - \min_{1\le k\le K} l_{ij}^k\right) \quad (3)$$

$$r'^k_{ij} = \left(r_{ij}^k - \min_{1\le k\le K} l_{ij}^k\right) \Big/ \left(\max_{1\le k\le K} r_{ij}^k - \min_{1\le k\le K} l_{ij}^k\right) \quad (4)$$

Secondly, the left score (*ls*) and right score (*rs*) can be calculated as:

$$ls_{ij}^k = m'^k_{ij} \Big/ \left(1 + m'^k_{ij} - l'^k_{ij}\right) \quad (5)$$

$$rs_{ij}^k = r'^k_{ij} \Big/ \left(1 + r'^k_{ij} - m'^k_{ij}\right) \quad (6)$$

Then, the total normalised value *nx* can be computed as:

$$nx_{ij}^k = \left[ls_{ij}^k\left(1 - ls_{ij}^k\right) + rs_{ij}^k \times rs_{ij}^k\right] \Big/ \left(1 - ls_{ij}^k + rs_{ij}^k\right) \quad (7)$$

Lastly, the crisp score a_{ij}^k of the transferred fuzzy assessment $\tilde{a}_{ij}^k$ can be computed as:

$$a_{ij}^k = \min_{1\le k\le K} l_{ij}^k + nx_{ij}^k \left(\max_{1\le k\le K} r_{ij}^k - \min_{1\le k\le K} l_{ij}^k\right) \quad (8)$$

Step 3: Normalising and generating the average matrix. Based on the above defuzzification, the new initial influence matrix of professional k is obtained as $A_k = [a_{ij}^k]_{n \times n}$. Here, the added normalisation step is applied to obtain the normalised initial influence matrix $D_k = \left[d_{ij}^k\right]_{n \times n}$ of professional k, which is the mapping from d_{ij}^k to [0, 1]. The commonly used method [32, 33, 36] is adopted for the normalisation as follows.

$$D_k = s_k A_k \tag{9}$$

where

$$s_k = \frac{1}{\max\limits_{1 \le i \le n} \sum_{j=1}^{n} a_{ij}^k} \tag{10}$$

Then, the average matrix A that represents the combined evaluation results from all professionals can be obtained, with the element $a_{ij} (1 \le i, j \le n)$ calculated as:

$$a_{ij} = \frac{1}{K} \sum_{k=1}^{K} d_{ij}^k \tag{11}$$

Step 4: Calculating the normalised direct and indirect influence matrix. The average matrix A can be normalised via equations (9) and (10) to calculate the normalised direct influence matrix D. Similar to obtaining the transition matrix of a Markov chain, the normalised indirect influence matrix ID can be computed from the normalised direct influence matrix D.

$$ID = D^2 + D^3 + \ldots + D^{\infty} = \sum_{h=2}^{\infty} D^h = D^2 \left(1 - D\right)^{-1} \tag{12}$$

where I denotes the identity matrix.

Step 5: Obtaining the total influence matrix. The total influence matrix T containing both direct and indirect influences can be acquired based on the summation of D and ID as:

$$T = D + ID = \left[D\left(1 - D\right) + D^2\right]\left(I - D\right)^{-1} = D\left(I - D\right)^{-1} \tag{13}$$

Step 6: Depicting the causal diagram. Suppose t_{ij} is the (i, j) element of total influence matrix T, then the sum of the ith row r_i (total influences of factor Fi on others) and the sum of the jth column c_j (total influences of others on factor Fi) can be calculated as:

$$r_i = \sum_{j=1}^{n} t_{ij} \tag{14}$$

$$c_j = \sum_{i=1}^{n} t_{ij} \tag{15}$$

The importance degree $r+c$ and net effect degree $r-c$ can be computed. For factor Fi, r_i+c_i is an index of the power of the influences per the factor (a measure of the importance of the factor), and r_i-c_i is an index of whether the factor has more impact on others or can be impacted by others (a measure of the net effect). The values of $r-c$ also categorise factors into cause and effect groups [33]. When the value of $r-c$ is positive, the factor belongs to the cause group. Otherwise, it belongs to the effect group. The causal diagram [32], also named as the cause-effect relationship diagram, can then be obtained by mapping the dataset of ($r+c$, $r-c$), which visualises the complex causal relationships among factors.

5.2. Data collection

As illustrated in Fig. 2, there are following four main components for the data collection in this study for different purposes. Details of the participants in interviews, survey and focus group meetings are presented in Table 3. Relevant information regarding construction robots and the explanation of influencing factors are provided.

- Literature review, brainstorming and informal expert interviews were performed to identify the initial influencing factors.
- Semi-structured expert interviews were conducted to verify the identified influencing factors. Twenty experts covering different stakeholder groups were selected by purposeful sampling to ensure the representativeness of the sample [41].
- A matrix-based questionnaire survey derived from the identified influencing factors was carried out for collecting required data for the modified fuzzy DEMATEL method. An example of the questionnaire is illustrated in Fig. 3. Eighteen professionals were selected by purposeful sampling [41] to ensure their expertise in building construction and construction robotics and Hong Kong industry, as well as being informative about the topic of interest. The professionals were asked to evaluate the influence of one factor on other factors using a 4-point scale (no, low, medium and high).
- Two focus group meetings were organised to verify the results from the modified fuzzy DEMATEL, each involved eight professionals.

Table 3 Details of the participants in interviews, survey and focus group meetings

Item	Descriptions	I*	Q	F	Total
Primary area of practice (professional)	Contractor (main and sub)	7	4	2	13
	Developer, Client and Investor	2	2	1	5
	Professional advisor	3	5	4	12

	Government and its agencies	3	1	3	7
	Manufacturer and Supplier	2	1	1	4
	Universities and professional bodies	3	6	5	14
Years of experience	5-9	3	7	4	14
	10-19	7	9	6	22
	More than 20 years	10	2	6	18
Total		20	18	16	54

*I=interviews; Q=DEMATEL questionnaire survey; F=focus group meeting

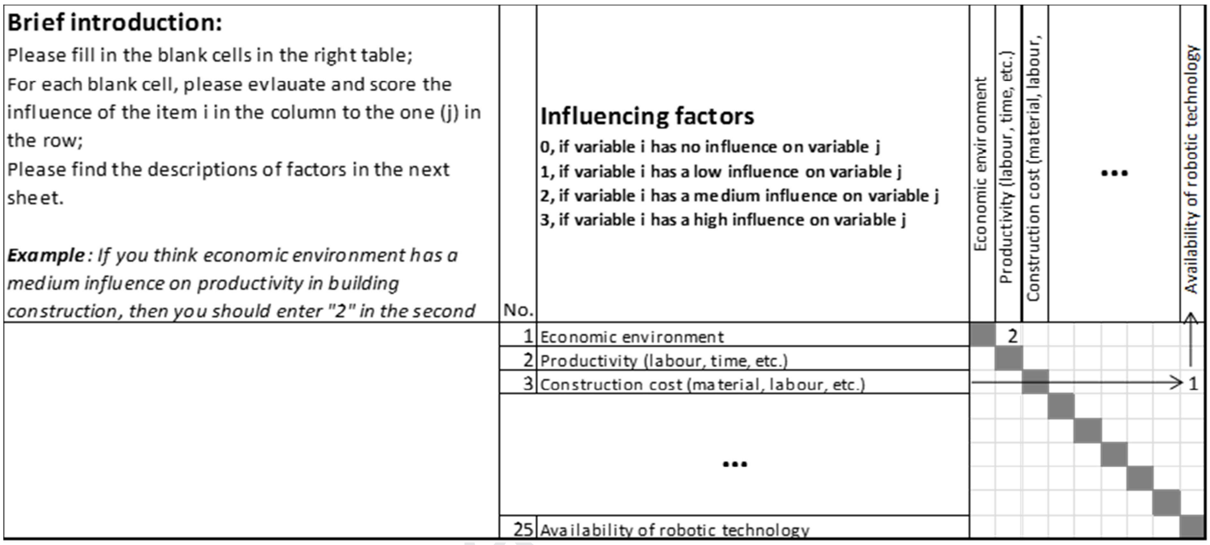

Fig. 3. An example of the questionnaire for performing the modified fuzzy DEMATEL

6. Results and analyses

The influencing factors were verified by relevant experts that are inclusive and influential to the future utilisation of construction robots for buildings in Hong Kong. Cronbach's α was used to estimate the reliability of the DEMATEL questionnaire [32]. The value of Cronbach's α from data on all the 600 assessed cells was 0.993 and it revealed that the questionnaire used is highly reliable (α>0.7).

According to the procedures introduced in the modified fuzzy DEMATEL method, the collected data from the questionnaire can be transferred based on Table 2 and defuzzied from equations (2) to (8). Then, the normalised direct influence matrix *D* and the total influence matrix *T* (Table 4) can be obtained from equations (9) to (13). Based on *T*, the sum of each row *r* and column *c* can be calculated using equations (14) and (15). The importance degree *r+c* and the net effect degree *r-c* can be computed to further determine the importance ranking and causal groups, as shown in Table 4. The causal diagram (Fig. 4) can then be drawn by mapping the dataset of (*r+c*, *r-c*). An exploratory analysis of factors is further provided regarding the importance and causality of the influence, based on Table 5 and Fig. 4, with consideration of the degree of importance, cause-effect group, *r* and *c* values. Key factors influencing the future utilisation of construction robots in Hong Kong can thereby be figured out.

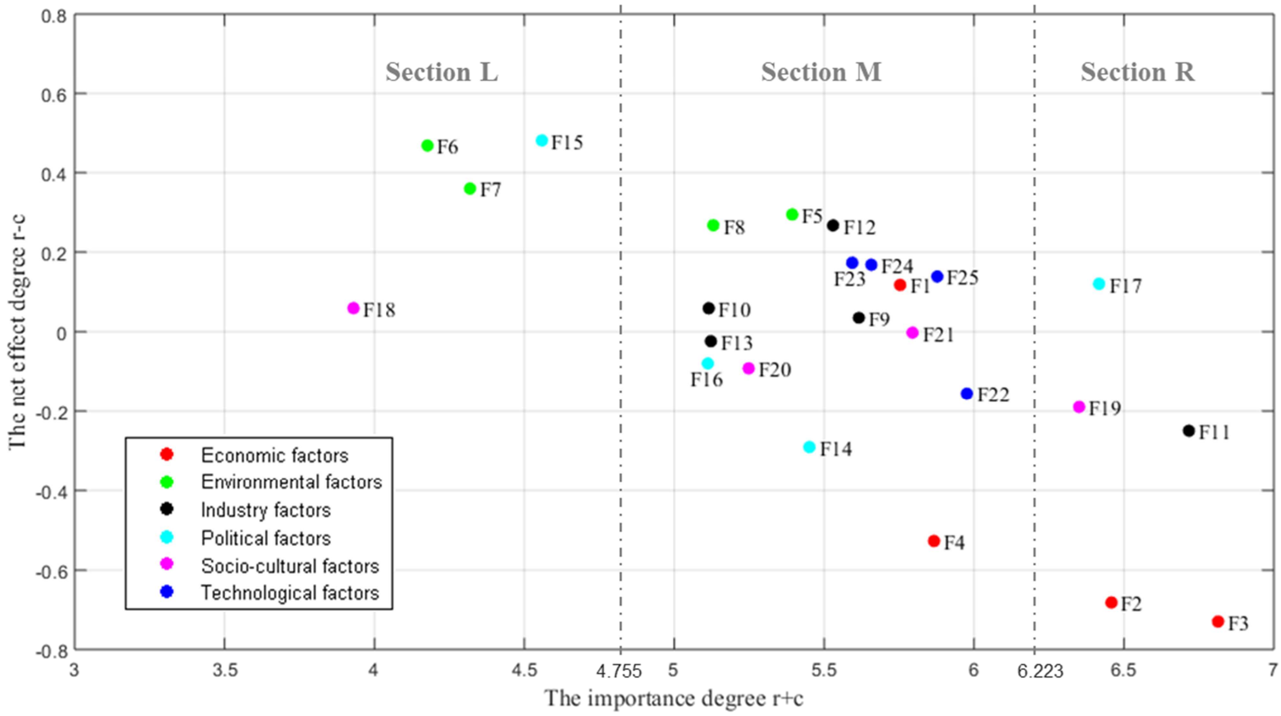

Fig. 4. The causal diagram of factors

Table 4 The total influence matrix T

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	F17	F18	F19	F20	F21	F22	F23	F24	F25
F1	0.104	0.156	0.129	0.118	0.127	0.090	0.123	0.148	0.098	0.145	0.116	0.125	0.131	0.122	0.118	0.134	0.104	0.156	0.129	0.118	0.127	0.090	0.123	0.148	0.098
F2	0.114	0.154	0.105	0.104	0.132	0.080	0.123	0.135	0.080	0.136	0.117	0.122	0.126	0.109	0.112	0.117	0.114	0.154	0.105	0.104	0.132	0.080	0.123	0.135	0.080
F3	0.115	0.161	0.118	0.119	0.128	0.086	0.124	0.137	0.091	0.136	0.115	0.124	0.131	0.114	0.115	0.122	0.115	0.161	0.118	0.119	0.128	0.086	0.124	0.137	0.091
F4	0.096	0.139	0.101	0.104	0.110	0.072	0.103	0.128	0.080	0.134	0.098	0.112	0.127	0.107	0.103	0.118	0.096	0.139	0.101	0.104	0.110	0.072	0.103	0.128	0.080
F5	0.105	0.149	0.109	0.114	0.108	0.099	0.095	0.131	0.083	0.141	0.110	0.113	0.127	0.106	0.104	0.113	0.105	0.149	0.109	0.114	0.108	0.099	0.095	0.131	0.083
F6	0.095	0.121	0.087	0.102	0.091	0.086	0.086	0.111	0.083	0.105	0.083	0.084	0.095	0.084	0.086	0.089	0.095	0.121	0.087	0.102	0.091	0.086	0.086	0.111	0.083
F7	0.086	0.125	0.088	0.087	0.092	0.095	0.082	0.108	0.066	0.112	0.091	0.085	0.095	0.085	0.088	0.091	0.086	0.125	0.088	0.087	0.092	0.095	0.082	0.108	0.066
F8	0.102	0.140	0.101	0.104	0.114	0.107	0.094	0.121	0.074	0.132	0.108	0.109	0.118	0.096	0.101	0.105	0.102	0.140	0.101	0.104	0.114	0.107	0.094	0.121	0.074
F9	0.106	0.150	0.113	0.101	0.113	0.075	0.108	0.129	0.075	0.140	0.114	0.124	0.139	0.115	0.116	0.117	0.106	0.150	0.113	0.101	0.113	0.075	0.108	0.129	0.075
F10	0.073	0.138	0.096	0.106	0.102	0.075	0.089	0.115	0.073	0.125	0.107	0.107	0.114	0.107	0.116	0.109	0.073	0.138	0.096	0.106	0.102	0.075	0.089	0.115	0.073
F11	0.127	0.121	0.119	0.135	0.134	0.102	0.118	0.142	0.094	0.149	0.131	0.136	0.145	0.129	0.132	0.133	0.127	0.121	0.119	0.135	0.134	0.102	0.118	0.142	0.094
F12	0.097	0.141	0.082	0.107	0.122	0.082	0.126	0.126	0.079	0.141	0.108	0.122	0.135	0.118	0.121	0.127	0.097	0.141	0.082	0.107	0.122	0.082	0.126	0.126	0.079
F13	0.108	0.134	0.094	0.072	0.095	0.072	0.086	0.113	0.088	0.119	0.101	0.100	0.113	0.104	0.105	0.107	0.108	0.134	0.094	0.072	0.095	0.072	0.086	0.113	0.088
F14	0.094	0.125	0.102	0.090	0.081	0.071	0.117	0.120	0.070	0.122	0.117	0.117	0.113	0.097	0.097	0.104	0.094	0.125	0.102	0.090	0.081	0.071	0.117	0.120	0.070
F15	0.092	0.135	0.090	0.097	0.095	0.057	0.082	0.117	0.065	0.120	0.099	0.100	0.106	0.091	0.090	0.099	0.092	0.135	0.090	0.097	0.095	0.057	0.082	0.117	0.065
F16	0.090	0.119	0.108	0.087	0.125	0.068	0.072	0.111	0.072	0.118	0.104	0.117	0.108	0.094	0.098	0.102	0.090	0.119	0.108	0.087	0.125	0.068	0.072	0.111	0.072
F17	0.121	0.151	0.116	0.101	0.131	0.082	0.117	0.107	0.084	0.154	0.121	0.130	0.140	0.138	0.140	0.147	0.121	0.151	0.116	0.101	0.131	0.082	0.117	0.107	0.084
F18	0.073	0.101	0.074	0.089	0.082	0.059	0.078	0.087	0.043	0.093	0.080	0.081	0.084	0.084	0.081	0.084	0.073	0.101	0.074	0.089	0.082	0.059	0.078	0.087	0.043
F19	0.118	0.157	0.121	0.117	0.126	0.094	0.114	0.143	0.082	0.111	0.119	0.131	0.145	0.128	0.133	0.134	0.118	0.157	0.121	0.117	0.126	0.094	0.114	0.143	0.082
F20	0.099	0.131	0.097	0.095	0.120	0.074	0.103	0.124	0.073	0.122	0.075	0.115	0.111	0.098	0.097	0.102	0.099	0.131	0.097	0.095	0.120	0.074	0.103	0.124	0.073
F21	0.103	0.138	0.107	0.102	0.130	0.077	0.121	0.132	0.078	0.137	0.114	0.087	0.129	0.109	0.114	0.112	0.103	0.138	0.107	0.102	0.130	0.077	0.121	0.132	0.078
F22	0.112	0.143	0.111	0.107	0.114	0.082	0.099	0.137	0.079	0.143	0.106	0.118	0.096	0.135	0.130	0.131	0.112	0.143	0.111	0.107	0.114	0.082	0.099	0.137	0.079
F23	0.111	0.144	0.108	0.106	0.119	0.078	0.100	0.147	0.076	0.153	0.109	0.123	0.135	0.087	0.137	0.132	0.111	0.144	0.108	0.106	0.119	0.078	0.100	0.147	0.076
F24	0.112	0.145	0.108	0.114	0.120	0.083	0.107	0.137	0.078	0.152	0.118	0.124	0.136	0.133	0.089	0.139	0.112	0.145	0.108	0.114	0.120	0.083	0.107	0.137	0.078
F25	0.117	0.142	0.110	0.113	0.120	0.079	0.108	0.146	0.077	0.148	0.113	0.123	0.133	0.128	0.129	0.092	0.117	0.142	0.110	0.113	0.120	0.079	0.108	0.146	0.077

Table 5 Degree of total influence of factors

	r	*c*	*r + c*	*r - c*	Importance ranking	Group*
Economic factors			**6.223**	**-0.455**		
F1: Economic environment	2.936	2.818	5.753	0.118	10	Cause
F2: Productivity	2.889	3.570	6.458	-0.681	3	Effect
F3: Construction cost	3.043	3.771	6.814	-0.729	1	Effect
F4: Initial investment cost and economic performance associated with robots	2.670	3.196	5.866	-0.526	8	Effect
Environmental factors			**4.755**	**0.348**		
F5: Demand for environmentally friendly buildings	2.844	2.549	5.394	0.295	16	Cause
F6: Land resource for building construction	2.323	1.854	4.177	0.469	24	Cause
F7: Climate change	2.339	1.979	4.319	0.360	23	Cause
F8: Awareness of environmental impacts of construction activities	2.699	2.431	5.130	0.268	18	Cause
Industry factors			**5.620**	**0.018**		
F9: Fragmentation and collaboration of the industry	2.826	2.790	5.616	0.036	12	Cause
F10: Unstructured, dynamic and unique site environment	2.588	2.528	5.115	0.060	20	Cause
F11: The scale of prefabrication	3.234	3.483	6.717	-0.249	2	Effect
F12: Globalisation in construction	2.899	2.631	5.530	0.268	14	Cause
F13: Building typology	2.549	2.573	5.122	-0.024	19	Effect
Political factors			**5.385**	**0.058**		
F14: Government labour policy	2.580	2.871	5.451	-0.290	15	Effect
F15: Charging for Construction Waste Disposal	2.520	2.038	4.559	0.482	22	Cause
F16: Government policy on foreign workers	2.516	2.596	5.112	-0.080	21	Effect
F17: Governmental support on robotics applications in construction	3.269	3.148	6.417	0.121	4	Cause
Socio-cultural factors			**5.331**	**-0.056**		
F18: Size and number of households	1.995	1.935	3.930	0.060	25	Cause
F19: Culture of innovation in the industry	3.081	3.270	6.351	-0.189	5	Effect
F20: Occupational safety & health performance	2.578	2.670	5.248	-0.092	17	Effect
F21: Work structure and organisation	2.896	2.899	5.795	-0.002	9	Effect
Technological factors			**5.776**	**0.081**		
F22: The uptake of information and communication technology	2.910	3.066	5.976	-0.155	6	Effect
F23: Technological difficulty to provide robotics performance features	2.883	2.710	5.594	0.173	13	Cause
F24: Ease of use of robots	2.913	2.745	5.657	0.168	11	Cause
F25: Availability of construction robotics	3.008	2.869	5.877	0.139	7	Cause

*: If *r*-*c*>0, the factor belongs to the cause group, otherwise it belongs to the effect group [32].

6.1. Importance analysis

The *r*+*c* value reveals how important a factor is to the entire system, thus facilitating the identification of vital factors. According to Table 5, economic factors, on average, have the highest *r*+*c* (6.223), followed by technological factors (5.776), industry factors (5.620), political factors (5.385) and socio-cultural factors (5.331), while environmental factors have the lowest (4.755). The highest and lowest *r*+*c* values of essential areas are then considered as thresholds to visually divide individual elements into three sections, as seen in Fig. 4. The right part ($r+c \geq 6.223$), referred to as Section R, includes F3, F11, F2, F17 and F19, which are the most critical factors that should be prioritised as key. The left part ($r+c \leq 4.775$), denoted as Section L, contains F18, F6, F7 and F15, which are the least critical ones, have no critical influence on the system and cannot be recognised as key. The remaining factors are in the middle section ($4.775 < r+c < 6.223$), named as Section M, among which are the most significant and influential ones which should be deemed as critical factors.

6.2. Cause-effect analysis

The influential power (net effect degree) of the factor is indicated by the *r-c* value which is applied in the DEMATEL method to determine the key factors. Individual elements are divided into cause and effect groups according to whether their *r-c* values are positive or negative. The causal factors are impulsive ones and exert a greater influence on others that are normally accepted to be valued. Conversely, the effect factors are reactive, and they tend to be more easily impacted by others making them less critical to some extent.

Concerning the factors in Section R, only F17 is causal, which implies its high influential impact upon others. The other four factors belong to effect group with negative *r-c* values. Nevertheless, the values of the influential impact index (*r)* of these vital effect elements are relatively high among all the factors, which suggests that they also have noticeable impacts on others. Therefore, considering the importance degree and the influential impact index, all factors in Section R are recognised as key.

For Section M, more emphasis should be placed on the causal factors, which dispatch more significant impacts on others than they receive. F5 has the highest *r-c* value in the section and a relatively high influential impact index *r*, although its importance score *r+c* is relatively low, it ranks top among the environmental factors. The cluster of key elements should be comprehensive enough to sketch the big-picture view of the future utilisation of construction robots. However, environmental factors should not be ignored. Therefore, F5 is also suggested as a key factor. Additionally, F25 is the most important causal factor with the highest influential impact index (*r)* in the section, which means it can play a pivotal role in influencing the future development and application of construction robots and it is identified as a key factor. The importance degree of F1 ranks second among all causal factors in Section M, but it is the lowest among economic factors. Compared to F2 and F3, F1 is less dominant in influencing the system and thus not considered as crucial. F24 ranks third regarding importance degree *(r+c)* and influential impact index (*r)* among causal factors in the section, showing its significance and influential force on the system. Since the importance of the technological area is high, F24 and F25 are regarded as pivotal factors too. Regarding the effect factor, F21 has the highest *r-c* value slightly below zero, which indicates that F21 is merely net affected by others. Furthermore, it also has a considerable impact on the system. Consequently, it is also considered as a vital factor with a compelling impact on the system. The remaining factors are not considered as key ones due to their relatively low influential impacts and importance degree.

Factors in Section L are all in the effect group. However, they all possess very low influential impact indices (*r)* and influenced impact indices (*c)*, which lead to their small importance scores (*r+c)*. Thus, they cannot have a critical influence on the system and are excluded in the set of critical factors.

6.3. Rationality and superiority of the modified fuzzy DEMATEL

Comparative tests were conducted using the traditional fuzzy DEMATEL and the modified fuzzy DEMATEL for method validation. The similarity of importance ranking and cause-effect grouping between methods can be used to illustrate the rationality of the new method [35]. Consistent results are obtained for two methods, indicating that the modified method is reasonable. Spearman's rank correlation coefficient [42] between importance ranking of two methods is 0.995 ($p < 0.01$), which reflects their high similarity. Besides, the modified fuzzy DEMATEL can also ascertain the reliability of the combined judgement and avoid the unequal weights caused by different judgment criteria, especially when the sample size is small. The effects of the assessment from every expert on the final factor ranking and grouping were tested in two methods by comparing the original results with results obtained when removing one assessment sample. The modified fuzzy DEMATEL provides better performance for acquiring consistent results with reduced samples. Statistically, Kendall's coefficient of concordance (*W*) [42] was used to show the ranking consistency of all testing samples. Results from the modified fuzzy DEMATEL (W=0.991, $p < 0.001$) has a higher Kendall's *W*, indicating a greater consistency than from the traditional fuzzy DEMATEL (W=0.980, $p < 0.001$). Although the testing reveals that results from both methods are consistent and reliable, one sole judgement interferes less with the combined judgement in the modified fuzzy DEMATEL than the traditional one, demonstrating its enhanced robustness and accuracy of the combination of judgement. In sum, the modified fuzzy DEMATEL is proved reasonable and superior.

6.4. Key influencing factors verification

Nine fundamental factors were determined from the modified fuzzy DEMATEL analysis and verified by two focus group meetings. The results were first presented, and then the importance of the factors was discussed within the multi-factorial network influencing the future of construction robots in practice. Two additional factors, F4 (initial investment cost and economic performance associated with robots) and F22 (the uptake of information and communication technology), are taken into consideration after the discussion. F4, albeit strongly affected by others, was argued to be the most direct indicator to assess the attractiveness of construction robots and allows a more intuitive understanding of the future scenarios. F22 is recognised as a critical foundation and a facilitator for construction robots under technology co-evolution in the construction industry, which may not be readily traceable from other factors.

To sum up, eleven key influencing factors covering the six influence areas were extracted: F2, F3, F4, F5, F11, F17, F19, F21, F22, F24 and F25. These are the most crucial ones to influence the future understanding, exploration and utilisation of construction robots for buildings in Hong Kong.

7. Discussion

7.1. Discussion on Influence areas

The results from the empirical study illustrate the potential impacts from different influencing areas on the future utilisation of construction robots for building in Hong Kong and reveal the complicated interactions of the factors. The empirical results suggest that economic and technological areas are, in general, most significant on the future use of construction robots, which contrary to past research findings [12, 20]. Besides, the systems perspective and examination of the causality among factors contribute to more noteworthy findings on influence areas, the implications of which are elucidated below.

Firstly, the economic area may act as a double-edged sword affecting the future use of construction robots in Hong Kong. The need for better economic performance (e.g. productivity) can force the industry towards robotics, but the continued focus on only the economic justification of technology [11] inhibit the real-world practice. This also explains the slow uptake of construction robots in real-world practice, where high uncertainties result in high risks. Construction robots are still in their infancy with uncertainties, and efforts should be channelled to factors beyond economic ones, for instance, technology development and transfer.

Secondly, the technological factors could play a dominant role in shaping the future uptake of construction robotics, consistent with previous studies [9, 24]. Greater use could be achieved not only through improved technological capability, interoperability and availability, but also from a more youthful, vibrant and knowledge-intensive industry influenced by technological development. However, individual technological factors are not the most important ones from the study, which may partly explain the minimal real-world adoption, albeit substantial technology development and advancement. There is a great need to focus more on the "soft" aspects and requirements from different stakeholders.

Thirdly, environmental pressures from landscape and regime could actively drive the utilisation of construction robots. Notwithstanding that environmental factors are identified as the least important ones, they are causal factors that could influence the future trajectory of others, thereby directly and indirectly impacting on the robotic applications. A few studies verified that the use of construction automation and robotics could improve sustainability in construction, but such an environmental consideration has not been widely embedded in current technology design and development [5, 25]. The results further demonstrated the influential power of the environmental area and its direct benefits gained from construction robots. Environmental attractiveness could actively promote future technology application. Such impetus might be further strengthened by the increasing emphasis on environmental aspects in performance metrics, which enables the emergence of a more sustainable technology than through conventional development or requirements engineering processes.

7.2. Discussion on key influencing factors

In terms of key influencing factors, eleven were identified to play a pivotal role in swaying the future use of construction robots owing to their high importance and net influence, together providing the big-picture view of the future robotic utilisation In particular, "construction cost" (F3), "governmental support on robotics applications in construction" (F17) and "the scale of prefabrication" (F11) are the most critical ones.

Firstly, “construction cost” was identified as the most important factors, which is commonly deemed as a critical driver for pushing construction down the automation and robotic path [12]. Hong Kong is facing pressing challenges in high construction costs [7], while the increasing pressure on the construction costs could be the top driver to shift the industry from relying on human workers to robotic labour in the future. However, as noted, it should be judged together with other factors to understand the plausible scenarios in future usage.

Secondly, “governmental support on robotics applications in construction” was identified as the most important factor in the causal group. Government plays an essential role to underpin the use of advanced technologies like construction robots concerning R&D investments, offering incentive schemes and formulating regulations and standards [1]. This has been the backup force to the robotics capabilities in countries like Japan and the USA [12]. As the largest developer in Hong Kong, the government could exert a broader influence on the future utilisation of construction robots. Specifically, the government should engage more directly and influentially to promote construction robots through adoption and demonstration in public projects or pilot projects, and should actively liaise with different stakeholders across the entire sector to gear up the technology development and knowledge sharing of construction robots.

Thirdly, “the scale of prefabrication” was identified as the second most important factor in the causal group, which has not highlighted in previous relevant studies. Prefabrication has played an essential role in building and construction in Hong Kong for decades, particularly in the public sector, as it has been applied to successfully achieve a significant reduction in time, waste and on-site labour requirements [6, 7, 24]. It is foreseeable that prefabrication will continue to develop, and the scale might increase in both the percentage and intensity of use. The influence on the uptake of robots can be multifaceted. It could positively affect the controllability of robots in the more regulated site environment, but may push robotics towards off-site manufacturing and limit the economic potential for on-site use. Thus, one potential technical direction of construction robots should address the issue of how to harmonically integrate on-site robotics with prefabrication or modularisation [28].

The results together also show that the successful shift of construction techniques towards robotics may undergo a socio-technical transition in the industry, influenced by the political support and environmental pressure from the landscape, regime level changes and technological advancement at the niche level, resulting in social and economic benefits in the building construction regime. So far, in the field of construction robotics, considerable attention has been directed to technology development [2-4], but little to the broader, non-technical aspects such as stakeholder acceptability, business models, societal functions, sustainability and marketability. Thus, more interdisciplinary efforts and systems approach are needed to foster future use and development solutions of construction robots.

8. Conclusions and future work

This research attempts to comprehensively explore and analyse the factors interactively influencing the real-world utilisation of construction robots, which have long been expected to open up new and enormous possibilities in the industry with substantial benefits. This paper has developed a modified fuzzy DEMATEL method and adopted a systems approach to investigate the factors influencing the utilisation of construction robots with the case of Hong Kong. Based on a multi-dimensional, multi-level systems exploration and synthesis, 25 influencing factors for the breakthrough of construction robots were identified and verified. A structural model of identified factors was developed to construct the questionnaire for data collection. The fuzzy DEMATEL method was modified to minimise the combination inaccuracies involved in different judgment criteria by professionals and provides results with improved robustness and accuracy, which was applied for factor analysis regarding interactions and importance. Notably, 11 key influencing factors were highlighted for focus. The most influential and prominent ones were found to be “construction cost”, “governmental support on robotics applications in construction” and “the scale of prefabrication”, further emphasising the need to link the development of construction robots to non-technological issues.

The findings demonstrate that influencing factors are highly interrelated, and their intertwined impacts may explain why the previous focus on technology advancement or technology-associated factors is not enough to fundamentally promote real-world practices. The findings further indicate that the successful shift of construction techniques towards robotics may undergo a socio-technical transition. Political support and environmental pressure from the landscape, regime level changes and technological advancement at the niche level provide impetus to the transformation, resulting in social and economic benefits in the building construction regime. These findings supplement previous studies by enriching the broad perspectives and extending the causal relationships among factors influencing the utilisation of construction robots.

In summary, this paper has made several fundamental contributions. Theoretically, a systems framework was presented to enable a holistic understanding of the influencing factors of the future utilisation of construction robots, which is illustrated by the case in Hong Kong, and may also apply to other countries and regions. Methodologically, the modified fuzzy DEMATEL method improves reliability and rigour of the combination of judgement and strengthens the analysis and findings, which could be readily applicable to other similar research problems. Practically, the empirical study in Hong Kong demonstrates the evaluation of key influencing factors and the exploration of causal relationships among factors, and thereby shedding new light on the future development and implementation of construction robots. More future studies are needed on the "soft" aspects and different stakeholders' requirements to drive the practical implementation of construction robots. Detailed utilisation scenarios to fit for societal movement are also recommended for future research, which could support strategic decision-making for different stakeholders. Besides, referring to the case of Hong Kong, later studies could construct the model of influencing factors to guide technological development in other cities and countries, which are in a similar state of transition from conventional to advanced construction technology and are pursuing the potential of construction robots.

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Appendix A. The full list of initial identified influencing factors

Table A.1. The full list of initial identified influencing factors

Influence areas	No.	Influence factors	Level*	Sources**
Economic (10 Factors)	1	Economic environment	L	[12, 22]
	2	The sharing economy	L	[10]
	3	Construction material cost	R	[1, 10, 21]
	4	Construction labour cost	R	[1, 10, 20, 21]
	5	Need for productivity improvement	R	[1, 6, 20-22]
	6	Need for quality improvement	R	[1, 25]
	7	Construction cost	R	[1, 10, 21]
	8	Tight project timeframes	R	[12]
	9	Initial investment cost associated with robotics	N	[12]
	10	Economic performance of construction robots	N	[6, 11, 12]
Environmental (8 Factors)	11	City's agenda for sustainable development	L	E
	12	Demand for environmentally friendly buildings	L	[10]

	13	Land resource for building construction	L	[5, 6]
	14	Climate change	L	[10, 26]
	15	Air quality	L	[5]
	16	Construction waste situation	R	[5, 10]
	17	Awareness of environmental impact of construction activities	R	[1, 5, 6, 10, 22, 26]
	18	Construction energy consumption situation	R	[5, 26]
Industry (10 Factors)	19	Fragmentation of the industry	R	[1, 6, 12, 22, 27]
	20	Globalisation in construction	R	[9, 10]
	21	Unstructured, dynamic and unique site environment	R	[6, 11,12]
	22	Repeatability of tasks	R	[12, 20]
	23	Diversity of tasks and work processes	R	[12, 27]
	24	Project delivery methods	R	[26]
	25	Internal and cross-industry collaboration	R	[1, 6, 22]
	26	The scale of prefabrication	R	[4, 9, 10]
	27	Unsuitable building design to support	R	[1, 11, 12]
	28	Building height and diversity	R	[10, 21, 22]
Legal (3 Factors)	29	Employment law (e.g. Occupational Safety & Health, working hours)	R	[10, 12, 27]
	30	Environmental legislation of construction works (e.g. Charging for Construction Waste Disposal)	R	[5, 12]
	31	Legal issues for robots (e.g. liability, responsibility)	N	B
Political (6 Factors)	32	Working Hours Policy	L	B
	33	Government policies on foreign workers	L	[12]
	34	Institutional barriers in project delivery	L	[12]
	35	Public procurement	R	[1, 6]
	36	Governmental support and incentives on robotics applications in construction	N	[1, 6]
	37	Relevant industry standards and guidance	N	[1, 27]
Socio-cultural (14 Factors)	38	Size and number of households	L	[10]
	39	Ageing population	L	[10, 12]
	40	Unemployment rate	L	B
	41	Population growth and urbanisation	L	[12]
	42	Gender gap of workers in the industry	R	[10]
	43	Culture of innovation in the industry	R	[10, 22]
	44	Need for safety and health improvement of workers	R	[1, 6, 20, 21]
	45	Willingness of the young generation to enter the industry	R	[10]
	46	Education and training	R	[10, 12, 22]
	47	Shortage of skilled labour	R	[6, 10, 20, 22]
	48	Age structure of the workforce in construction	R	[6, 10]
	49	Awareness of technology by the industry	N	[12]
	50	Awareness and acceptance by workers and workers union (mind set)	N	[11, 12]
	51	Managerial apprehension of robots	N	[11]
Technological (14 Factors)	52	Global penetration of construction robotics	L	B
	53	R&D efforts on construction innovations (robots)	L	[12]
	54	The development of artificial intelligence	L	[10]
	55	The development of sensor technology	L	[10]
	56	Architectural freedom	R	[21]
	57	The uptake of information and communication technology in construction	R	[10]
	58	Technological difficulty to provide robotics performance features	N	[9, 11, 12, 20]
	59	Technology complexity	N	E

60	Technology compatibility	N	E
61	Technology interoperability	N	[6, 9, 11]
62	Size, weight and power supply of robotic technology	N	[9, 11]
63	Ease of use of robotics	N	[3, 9, 12]
64	Relative advantage of robotics	N	[9]
65	Availability of construction robotics	N	[12]

*: L – landscape level; R – regime level; N – niche innovations level
**: E: additional ones from expert interviews; B: additional ones from brainstorming

Appendix B. The definition of notations

The definition of key notations used in the modified fuzzy DEMATEL method are summarised below.

n: the total number of influencing factors from F1 to Fn

K: the total number of professionals in the evaluation

x_{ij}^{k}: the influence score given by professional k that represents the judgement of influence of factor i on factor j

$X_k = [x_{ij}^{k}]_{n \times n}$: the initial influence matrix representing the pair-wise influence of factors evaluated by professional k

$\tilde{a}_{ij}^{k} = (l_{ij}^{k}, m_{ij}^{k}, r_{ij}^{k})$: the triangular fuzzy numbers represent the influence score x_{ij}^{k} by professional k

a_{ij}^{k}: the calculated crisp scores of fuzzy numbers $\tilde{a}_{ij}^{k}$ represent x_{ij}^{k}

$A_k = [a_{ij}^{k}]_{n \times n}$: the new initial influence matrix from professional k

$D_k = [d_{ij}^{k}]_{n \times n}$: the normalised initial influence matrix from professional k

A: the average matrix of the normalised initial influence matrices from K professionals

D: the normalised direct influence matrix from K professionals

ID: the normalised indirect influence matrix from K professionals

T: the total influence matrix from K professionals

t_{ij}: the (i, j) element of total influence matrix T

r_i: the sum of the ith row of total influence matrix T that denotes the total influences of factor Fi on others

c_j: the sum of the jth column of total influence matrix T that denotes total influences of others on factor Fi

r_i+c_i: an index of the power of the influences per the factor (a measure of the importance)

r_i-c_i: an index of whether the factor has more impact on others or can be impacted by others (a measure of the net effect)

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Highlights:

- A systems perspective is applied on the future utilisation of construction robots.
- A modified fuzzy DEMATEL method is proposed for influencing factor analysis.
- Eleven key influencing factors are identified to shape the trajectory of construction robots' utilisation.
- Environmental pressures were found to actively drive the utilisation of construction robots.
- Broader, non-technical factors are critical to the future utilisation of construction robots.

Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: