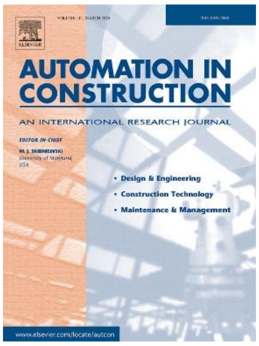

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Structuring the Context for Construction Robot Development through Integrated Scenario Approach

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Abstract: The technological development of construction robots is underway globally. However, current development activities face significant uncertainties, particularly in terms of the definition and management of system requirements, which are primarily based on vague assumptions about the future. Thus, a new tool is required to grasp how construction robots—and their surrounding ecosystems—will be used. This research adopts an unprecedented scenario-based approach to develop and analyze future alternatives for construction robotics in a systematic manner. Hong Kong "toward 2035" is used as an initial test case, and four scenarios of the robot ecosystem, i.e., "Bottleneck," "Age of Iron Worker," "Dynamic Co-evolution of Robotization and Modularization," and "Rise of the Robots," are developed from evidence-based analysis. Scenarios highlight the crucial role of workers for construction robot utilization. Driving forces, opportunities, and challenges are identified for elaborating strategies under each scenario. The integrated scenario approach and findings lay an important foundation for systems engineering processes in construction robotics to develop a new tool for structuring system context and specifying system requirements.

Keywords: construction robotics; construction technology; technology forecasting; scenario techniques; systems engineering.

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1 Introduction

The building and construction industry is facing increasingly grave challenges such as cost escalation, skill mismatch, and an aging workforce. This trend is particularly exacerbated in high-tech-focused, high-density, and high-wage metropolitan areas, such as Hong Kong, where the industry is struggling to satisfy the ever-increasing demand for construction [1]. In such contexts, the ability of conventional construction methods to cope with the growing complexity of construction and meet the associated demands for productivity, quality, safety, and sustainability have reached their limits [2]. Construction robotics is considered a promising innovation to address this challenge and reform the industry, which has triggered a plethora of global research and development (R&D) efforts for decades [3]. Many prototypes have been developed since the 1980s, providing evidence on the ability of construction robots to assist in conducting dangerous, monotonous, or tedious construction jobs more efficiently and accurately [4].

Although construction robots promise many benefits, multiple barriers continue to hinder real-world applications. Examples include professional skill shortages; risk-averse mentality coupled with industrial potential of complex technology awareness [5]; cultural resistance against the adoption of innovative technologies [6]; and high capital costs and additional setup time of robotic equipment [4]. These barriers lead to uncertainties and eventually allow many possible development lines for next-generation robotic construction. Previous researchers have attempted to predict the future use and utilization of construction robots [4, 7]. However, there is still a lack of systematic exploration of possible future scenarios with multiple alternatives from a systems perspective. In addition, none of these studies have holistically considered the sociotechnical context of construction robots that would surround and determine the application of such systems. The lack of such studies poses a major challenge for both the early stage conception of construction robots and the associated systems engineering processes [8]. This is because key development aspects (e.g., requirements engineering, business strategies, and degree of automation) that set the stage for the development of construction robotic systems are based on vague assumptions about how the future industry will be and what kind of construction robots will be developed. This situation is aggravated by the fact that construction robotics is not yet an established field, lacking implicit design experiences or robust data from previous developments and applications. Therefore, it is essential to develop new tools to project the future solution space (the set of all possible solutions) of construction robots over a given period.

This paper aims to develop a new tool for the systematic development, exploration, and analysis of the future utilization of construction robots in a given industrial environment (ecosystem) based on the application of a scenario approach. Scenario approaches allow users to make assumptions about the mid- to long-term future [9, 10], i.e., a period 5–15 years ahead, which can represent and cover the applicable development cycles of construction robotics. Scenario approaches have successfully been used and adapted to a variety of industries, such as automobile and consumer goods, where long-term projections are required for improved planning of fundamentals and decision-making on future product lines [9, 10]. In this study, the authors transfer and adapt the basic scenario approach as a new tool in the field of construction robotics to structure the development context as the fundamentals of systems engineering processes of construction robots. Hong Kong is used as an initial test case setting for the study, representing a locally confined and complex industrial ecosystem with a mature construction industry [11].

The remainder of this paper is structured as follows. Section 2 outlines the background of the study. Section 3 describes the integrated scenario approach developed for and applied in this study. Section 4 introduces the scenario creation phase that develops the scenarios from the prognosis and clustering of key influencing factors and then describes them as snapshots of potential scenarios. Section 5 presents the scenario transfer phase that further identifies contextual challenges and opportunities to generate strategic planning for stakeholders under each scenario. Section 6 discusses the contributions and limitations of the study. Section 7 concludes the paper and proposes future research directions.

2 Background: concepts, advance beyond the state of the art, and the test case

To set the stage for the methodological approach, this section introduces the relevant terms and concepts in the context of construction robotics, analyzes the state-of-the-art studies on the future of construction robots and forecasting techniques, and introduces the initial test case setting (Hong Kong).

2.1 Key concepts in construction robot engineering

While construction automation and robotics generally cover a broad spectrum of technologies, this study exclusively focuses on construction robots. Although a consensus has not yet emerged on a clear definition of a construction robot [7], it often refers to more sophisticated and intelligent types of machinery [12] with robotic features. To facilitate the requirement analysis for systems design and development of construction robotics [12], a clear categorization is essential to thoroughly understand and differentiate the development requirements and goals for construction robots [19, 23].

Therefore, in this study, a two-dimensional perspective for the categories of robots for buildings (Fig. 1) is proposed considering the building life-cycle and the level of task integration. Usually, construction robots are, to some extent, task-specific (concrete finishing, wall painting, bricklaying, facade cleaning, demolition, etc. [4, 13, 14]). In addition, new forms of robots have emerged, such as adding and integrating aerial approaches [15], exoskeletons for power augmentation [16], additive manufacturing technologies [17], collaborative robots [18], and humanoid robot technology [19]. Such robots help construction workers with more general tasks and can be considered to be task-generic. Larger, complete systems are referred to as integrated automated and robotic systems or automated/robotic on-site factories [20, 21].

The development and systems engineering process for construction robots requires a domain-specific, multidisciplinary, and phased approach, which was first conceptualized by Hasegawa et al. [22] and Maeda [23], and then later advanced and developed by, for example, Bock and Linner [24] and Linner et al. [25]. As systems engineering gains prominence in other industries [26], the successful development of construction robots over subsequent, linked, and iterative steps is dependent on a thorough understanding and definition of the dynamic contexts surrounding such systems, as well as the “informed” inference and management of associated requirements.

[insert Fig. 1 here]

2.2 Previous systematic studies on the future construction robots and novelty of a scenario approach

Studies on the future of construction robots and possible future developments have focused primarily on existing barriers to implementation and future promises. Warszawski and Navon [27] identified four fundamental reasons for the minimal success of robots in building construction: insufficient development, unsuitable building design, inadequate economic justification, and managerial barriers. In response, they proposed strategies for more efficient future implementation. Mahbub [7] analyzed and ranked the barriers to infiltrating construction automation and robotics in Japan, Australia, and Malaysia with different levels of usage, and briefly speculated on the plausible future. Bock [2] categorized the future trends in construction automation and robotics into five areas: robot-oriented design, robotic industrialization, construction robots, site automation, and ambient robotics. Quezada et al. [28] explored the future of the construction workforce in Australia and discussed the impacts of construction automation and robotics on future labor. Bogue [13] discussed and illustrated the current uses and potential role of robots in improving the construction industry, with examples of different classes of robots. These studies provide insightful understandings of the application challenges or future prospects of construction robots, with focus on the details of promising technologies. However, there are few studies that examine the future potential of construction robots in a comprehensive and systematic manner.

Multiple sociotechnical issues could lead to uncertainties and eventually allow many possible deployments for robotic construction. The possibility of potential scenarios to reduce ambiguity and understand complexity in the design of construction robots is therefore of great importance, but remain unexplored. In this regard, a scenario approach

[9, 10] would be key to holistically understand and systematically develop scenarios, i.e., behaviors and future states of the robotic ecosystem to which the requirements and development activities for robots shall be subsequently oriented. Such approaches could provide adequate information to support the system engineering processes of construction robots. Construction robotics is not yet an established field and lacks know-how and experience about basic scenarios and requirements. Thus, domain-specific forecasting techniques would provide developmental and structural contexts as well as allow design inputs. This study takes an initial step toward addressing this gap by providing, for the first time, systematic scenarios to examine and structure the future robotic ecosystem context of construction robots. Specifically, a scenario approach integrating qualitative and quantitative methods was developed and applied to systematically develop the possible narratives and solution spaces for the future of construction robots, using Hong Kong as a test case. The scope of this study is limited to building work; consequently, robots working in civil engineering projects are excluded. The scenario approach can serve as the initial steps toward an effective tool to inform and guide construction robot developments, reducing requirements uncertainty by establishing the structure and formalizing the scenarios from which design inputs can be inferred for the later systems engineering process.

2.3 Initial test case setting: Hong Kong construction industry

The building and construction industry is fundamental to urban growth and plays a pivotal role in achieving the rapid economic development of Hong Kong [11]. The industry is characterized by a small group of large local contractors, who make up a large number of small-sized local construction companies that support the high level of subcontracting with the support of many overseas contractors [29]. Concerning the building sector, work can be classified by building typologies into residential and nonresidential, or public and private [30].

Over the years, construction companies in Hong Kong have also developed their expertise in qualified performance and gained a reputation in such a large and fast-growing market. However, along with these achievements, the industry faces challenges on many fronts. The ever increasing demand for labor, accompanied by skills mismatch (projected shortfall in skilled construction workers from 5,000 to 10,000 between 2019 and 2023) and aging labor force (37.7% of skilled and semi-skilled construction workers were above the age of 55 in 2018) poses significant risks to the realization of a productive industry [11, 31]. Moreover, the escalation of construction costs—Hong Kong had the third-highest construction costs worldwide in 2018—and land shortage (predicted shortfall of 1,200 hectares toward 2030) have made it difficult for construction companies to make a profit [11, 32]. Site safety performance in terms of fatalities (22 industrial fatalities in 2017) and accidents (3902 industrial accidents in 2017) remain unsatisfactory [11]. The impact of construction work on the environment and general public in Hong Kong is in a critical state in terms of carbon emissions, waste demolition, noise pollution, and disturbance to surrounding areas [33]. All these issues are severely hindering the sustainable development and continuous prosperity of the industry.

The industry has explored advanced technologies and intelligent approaches to tackle the challenges and thrive in dynamic circumstances. The conception and implementation of advanced construction technologies (e.g., [11, 34, 35]) have been facilitated by its key actors throughout the last couple of years. For example, it is a pioneer in prefabrication since the early 1970s, yielding significant economic and environmental benefits [36], and is currently promoting the adoption of modular integrated construction [34, 37] as a more advanced method for off-site construction. Major local construction companies are progressively investing in innovative technologies such as robotic arms, exoskeletons, and 3D printing for construction, which hugely invigorate and inspire the remainder of the industry [38]. Meanwhile, the government has provided continuous financial and non-financial support to the industry to create a more fertile environment for innovation and technology R&D. The Construction Industry Council (CIC), as a statutory body, launched the Construction Innovation and Technology Application Centre in 2017 to accelerate information sharing and practices on the latest construction technologies [39]. Furthermore, CIC also established a new institute in 2018 to cultivate higher caliber and professional practitioners for the construction industry [1].

In short, for this study, Hong Kong is considered a valuable test case. Firstly, the significance of the built environment has always been highlighted by the government as the overwhelming theme for future development [1, 40]. Secondly, Hong Kong as a high-rise, high-density metropolis is facing severe labor and cost challenges that are strongly linked to unperformed productivity, which are also global problems especially in modern cities [11]. These challenges create the ideal environment for utilizing construction robotics in Hong Kong and similar cities or economies dealing with increasing density and urbanization, a growing number of high-rise buildings, an aging workforce, and labor shortage. Despite regional differences, the Hong Kong case can be considered as a global reference for understanding the essential elements (e.g., conceptual, functional, operational, and environmental requirements of system development) of construction robots against different future motives and challenges.

3 Methodology

Scenario approaches are widely applied to predict and understand the potential outcomes of technological changes such as directions, rate, characteristics, and impacts, incorporating the uncertainties of complex long-term development for investment and policy strategizing [9]. The term “scenarios” has different definitions [10]. In this study, a scenario is defined as a plausible combination of alternative developments in critical dimensions [41]. The inherent benefit of the scenario approach is the consideration of a range of possible future alternatives, thereby allowing stakeholders and practitioners to have alternative views of the future to properly define the requirements and reduce the risks of making the wrong decisions [42]. This is preferable for this study, which could provide contextual awareness of the potential alternatives for construction robots in future utilization, thereby supporting the strategic requirements for the definition and decision-making by different stakeholders.

There is no universal scenario method [43]. In order to provide rich and complicated profiles to establish potential prognoses theoretically and systematically, scenario approaches have been conducted differently based on the backgrounds, goals, and steps applied [42]. Previous scholars [42, 44] have compared various scenario approaches and summarized the fundamental steps to construct scenarios. Besides, since the scenario approach heavily hinges on the accuracy of assumptions, several strategies of improvements have been proposed by integrating other methods like mathematical models [45], system dynamics [46], and fuzzy theory [47] to improve the scenario formation and description. Nevertheless, little attention has been paid to improve the identification of key influencing factors in the scenario approach, which is one fundamental step to provide the critical components for the scenarios. Cross-impact analysis (CIA) [48] and complementary qualitative analysis [42] are standard methods for the identification of key influencing factors. However, CIA considers only the direct impacts of factors to capture a causal relationship analysis, and complementary qualitative analysis is inherently subjective to ensure consistent results [42, 48]. A more reliable identification of key influencing factors through causal relationship analysis could be achieved with the consideration of both direct and indirect impacts of factors in a quantitative manner. Consequently, this paper proposes using the decision-making trial and evaluation laboratory (DEMATEL) method to identify key influencing factors by analyzing interdependence between factors in a causal diagram and providing contextual understanding in scenarios [49]. A modified fuzzy DEMATEL method (see in Appendix A) is proposed, which integrates the fuzzy set theory into DEMATEL [50] with further modification to address the ambiguous issues within human judgments and different judgment criteria.

Based on previous studies [9, 42], an integrated scenario approach was applied as a new tool to structure the context for future construction robot development. The approach consists of three phases, with eight steps as follows (Fig. 2).

[insert Fig. 2 here]

- *Step 1 - Define the object of analysis*: The first step is to define the object of analysis and scenario field. In this study, the focus is on the utilization of construction robots for buildings in the context of Hong Kong within a time window of 18 years from the baseline year (2017). The relevant definitions and background have been outlined in the background section.
- *Step 2 - Identify influencing areas and influencing factors (IFs)*: A multidimensional, multilevel, sociotechnical conceptual framework was proposed based on the

multilevel perspective (MLP) theory [51] and the PESTEL (political, economic, sociocultural, technological, environmental, legal) model [6]. Drawing on the framework, the scenario field was divided into influencing areas and the IFs in each area were identified based on a holistic literature review and brainstorming. Semi-structured interviews with 20 experts were conducted to verify the identified IFs. Purposeful sampling was used to ensure the sample covering different stakeholder groups for representation. Fig. 3 illustrates the whole procedure in this step.

[insert Fig. 3 here]

- *Step 3 - Identify key influencing factors (KIFs)*: KIFs can be determined by pairwise influence analysis of the IFs. A modified fuzzy decision-making trial and evaluation laboratory (DEMATEL) method was proposed and applied to analyze the causal interrelationships between the IFs, and identify KIFs [52]. Data were collected through a DEMATEL questionnaire survey (see Appendix B) of 18 professionals using purposeful sampling. The identified KIFs were further validated and finalized by two focus group meetings involving 16 professionals. The whole procedure in this step is illustrated in Fig. 4.

[insert Fig. 4 here]

- *Step 4 - Derive projections of KIFs*: The purpose of deriving KIF projections is to obtain the fundamental components for developing plausible scenarios. The appropriate number of projections bears on the number of scenarios to be created [42]. Typically, 3 to 5 scenarios are recommended by most researchers [43]. In this study, a four-scenario outcome was envisaged, since a three-scenario framework could pose the risk of centering on the middle scenario, and five scenarios may not be justifiable [43]. Possible developments of each KIF were projected within the target time window based on documentation review and analysis, and then examined and finalized through two focus group meetings. One meeting focused on technology while the other on the application environment. The participants were asked to either select or initiate new KIF projections based on the referential ones provided by the research team. The past development and status quo of each KIF were briefly introduced, with participants tasked with forecasting the most relevant factors according to their professional backgrounds. Fig. 5 illustrates three examples of how to develop the KIF projections. KIFs represented as red dots from IFs were projected, respectively.

[insert Fig. 5 here]

- *Step 5 - Cluster projections*: The purpose of clustering projections is to create raw scenarios from the combination of projections that are most likely to occur simultaneously. The procedure in this step is outlined in Fig. 6. The consistency matrix [9], with pairwise comparisons of consistency, was applied to cluster compatible projections into bundles. In each case, all projections of a factor were first juxtaposed, element by element, with all projections of the other factors. The consistency assessment was based on a five-point scale with 5 = strong consistency (strong mutual support) and 1 = strong inconsistency (complete opposition). Then, projection bundles were obtained with all possible combinations of KIF projections (each bundle containing one projection from each KIF), and a consistency value was calculated and ranked for each bundle. The most consistent bundles can then be obtained based on the consistency value with a defined quality level for calculation. Supported by the ScMI AG software [53], similarity, referred to as "distance," can be calculated between any two bundles according to differences in projections, where one different

KIF projection is calculated as "1." Similar projection bundles (each bundle containing one projection from each KIF) are clustered into groups based on connectivity-based clustering (hierarchical clustering) to develop the raw scenarios.

[insert Fig. 6 here]

- *Step 6 - Describe scenarios*: The raw scenarios were further interpreted and described pictorially to create the final scenarios, considering the trends of KIFs in the raw scenarios and their impacts. Scenarios could then be described in terms of what and how construction robots will be utilized for buildings in Hong Kong within the targeted timeline, considering the sociotechnical configuration of the industry. The developed scenarios were further verified by experienced and senior professionals from building contractors through a questionnaire survey in terms of probabilities and additional concerns, considering that contractors are direct adopters of construction robots.
- *Step 7 - Analyze disruptive events*: Disruptive events, also known as "black swan" events, are future events with low probabilities of occurrence but with high impact on other events and the environments in which they occur. The possible disruptive events were identified, and their effects on scenarios were discussed.
- *Step 8 - Elaborate strategies*: Implications of the scenarios were explored with regard to driving forces, opportunities, and challenges under each scenario. Strategies for different stakeholders under each scenario were also developed accordingly.

The study involves data collection through literature review and brainstorming by the research team, as well as interviews: two questionnaire surveys and focus group meetings with professionals in different steps. Details on the professionals who participated in interviews, surveys, and focus group meetings in relevant steps are presented in Table 1.

[insert Table 1 here]

Aligned with Fig. 2, the results and findings of scenario creation and scenario transfer are presented in Sections 4 and 5.

4 Scenario Creation

This section introduces the Scenario Creation phase, where scenarios are created to describe the possible future use of construction robots for building construction in Hong Kong, according to the methodology presented in Section 3.

4.1 Identify influencing areas and influencing factors

As described in Section 3, a holistic literature review, brainstorming, and expert interviews were undertaken to identify influencing areas and IFs based on the conceptual framework developed from MLP theory [51] and PESTEL model [6]. The MLP has emerged to explain and analyze socio-technical transitions as interactive processes of changes in niches, regimes and landscape levels [51] and PESTEL is a useful analytical tool to examine socio-technical factors in a multidimensional way [6]. The framework could, therefore, allow a multidimensional multilevel analysis of a broad range of factors affecting the successful transition of construction robots into the industry, as niche developments in their infancy. Drawing on the framework, a critical literature review was conducted on relevant studies (e.g., [2-4, 7, 12-14, 23, 25, 26, 54, 55]), through which 65 IFs were initially identified and later reduced to 25 IFs (after combination and refinement, see Appendix B) according to economic, environmental, industry, political, sociocultural, and technological aspects [52]. The identified IFs were verified by relevant experts as inclusive and influential to the future utilization of construction robots for buildings in Hong Kong.

4.2 Identify key influencing factors

Through the aforementioned process of identifying KIFs, KIFs can be determined through pairwise influence analysis of IFs using the modified fuzzy DEMATEL method. The 25 IFs were assigned to formulate the matrix-based DEMATEL questionnaire survey (see Appendix B) for KIF analysis and verified using focus group meetings [52]. Table 2 outlines the identified 11 KIFs, together with their descriptors for making projections.

[insert Table 2 here]

4.3 Derive projections of key influencing factors

To provide evidence for projection development, the past development and status quo of each KIF were investigated through the review of relevant literature and documents [32, 56-58]. By considering government planning and policies [40, 56], up to four possible developments for each KIF were projected in the target time horizon by the research team as the reference point. The proposed projections were examined and finalized through two focus group meetings. After integrating perceptions from professionals, a full list of KIF projections was formulated, as shown in Table 3. Some factors have been described as having only one clear projection, such as "demand for green buildings," with consensus on an increased state.

[insert Table 3 here]

4.4 Cluster projections

All plausible combinations of the future were constructed based on consistency analysis, while the most consistent projection bundles were obtained according to the consistency values, which were clustered into groups based on the similarity of developing the raw scenarios. The results of raw scenarios are presented in Fig. 7. Each circle represents a projection bundle, and the similarity of 97 projection bundles defines the spatial location. All projections in a bundle in one cluster were combined and alternative projections were identified in raw scenarios based on the calculated occurrence proportion *p* in the scenario [9]. The alternative projections were validated in the next step according to their fitness to scenario descriptions.

[insert Fig. 7 here]

4.5 Describe scenarios

Whilst it is impossible to accurately predict how construction robots will be utilized in the future, the scenario narratives indicate areas in which a reasonably plausible future may be illustrated through certain influencing conditions. Therefore, for each scenario, a sense of the context for technology utilization is offered, considering technological features, the depth and breadth of usage, and essential characteristics of the industry. Each raw scenario as a projection cluster in Fig. 7 is given a characteristic name. Detailed descriptions are provided below.

4.5.1 Scenario 1: Bottleneck

In this scenario, the industry will experience few disruptive changes with construction robots, which have not been well developed and applied as expected owing to the multiple "bottlenecks" of economic justification, technology usability and availability, and industry culture and structure. In short, they are not appealing enough to the construction industry in Hong Kong. Traditional trades will remain in high demand. Although there is increasing use of ICT and prefabrication, the industry will continue suffering from the issues of an aging workforce, scarcity of skilled labor, and high construction costs. Despite the rising awareness in sustainability and increasing demand for green buildings, primary attention will be paid to the operation stage, and environmental issues during the construction stage will remain. Construction productivity may even decrease, as more man-hours may be needed for completing the same work, compared with the status quo, owing to the increasing geographical difficulties, as well as increased quality and functional requirements. The government may tighten the financial support for construction robotics and focus more on other innovative technologies for construction.

4.5.2 Scenario 2: Age of Iron Worker

This scenario outlines a continuously improving industry centered on robot-assisted construction workers, like "Iron Men." BIM and many other ICT tools will be substantially used to facilitate the digital transformation of the industry, laying the groundwork for implementing robotics. Construction robotics will begin to emerge in some applications to support human workers, facilitated by technological advancement and increasing labor challenges. Most likely, the industry will utilize well-developed, general-purpose robots, like exoskeletons and drones, to assist the aging workforce and manage the labor shortage. Furthermore, heavy machinery and equipment will be developed toward highly integrated, automated, and intelligent levels. Risk aversion across the sector will continuously shape a conservative culture, such that the industry practitioners will remain reluctant to use innovative technologies that radically change conventional practice, like humanoid or autonomous robots, highly integrated on-site robotics factory.

4.5.3 Scenario 3: Dynamic Co-evolution of Robotization and Modularization

In this scenario, the use of construction robots is strongly linked to increasing modularization and prefabrication, which will provide a substantial boost to construction productivity and sustainability, as well as ease the skilled labor shortage. The uptake of modularization or increasing rate of prefabrication could somewhat restrain the demand for extensive use of on-site robots; however, these also create a more controllable and favorable environment which favors the use of certain kinds of robots or systems to assist or perform work such as site management, logistics, material handling, and on-site assembly. The government as the main client broadly encourages off-site construction in government procured projects, e.g., for achieving greater efficiency in delivering massive housing programs, while clients in the private sector become the leading force for automation and robotics in particular projects. A fundamental change may exist in traditional patterns for building construction with entirely different on-site needs for human labor, but very likely, the future will witness a “dynamic co-evolution of robotization and modularization.”

4.5.4 Scenario 4: Rise of the Robots

This scenario represents a future in which the Hong Kong construction industry is aggressively pursuing robotic construction technologies to deal with sociotechnical challenges, thus contributing to a productive, sustainable, and knowledge-intensive sector.

However, this “rise of the robots” could generate disruptive changes. Technologically, construction robots will be maturing at an impressive rate with increased usability, underpinned by advancements in sensor technology and artificial intelligence (AI). Hong Kong, as a vibrant adopter, will benefit from its positive socio-technical environment for construction robots to attract international investors and technology developers, while its intrinsic technological capability will also be boosted with increased R&D activities. Owing to the high availability of technology, along with the reduced capital cost and payback period, a diverse array of on-site robots or even those in the form of a highly integrated robotic site will be utilized for building construction and deconstruction in Hong Kong. The government will have provided sufficient financial support and initiated incentive schemes in robotics research and applications in construction. Specific guidance and standards for construction robots will have also been developed. The industry will undergo major changes in the allocation of labor and work profiles.

4.5.5 Perspectives on future scenarios by building contractors

The probabilities of the four developed scenarios were further assessed by 94 professionals from different building contractors in Hong Kong using a questionnaire survey. Respondents were asked to assess the probability of each scenario regarding the use of construction robots in 2035 in Hong Kong, described by critical trends, using a five-point Likert scale, and to state their additional concerns in their response to an open-ended question. As seen in Fig. 8, the four scenarios were generally agreed as probable (mean>3), with higher probability of scenario 2 (Age of Iron Worker) and scenario 3 (Dynamic co-evolution of Robotization and Modularization). The responses to the open-ended question are summarized as follows.

- The future utilization of construction robots may not change if the “no change no fault culture” remains across the sector, which leads to fear of failure by using construction robots.
- There should be more support from developers and the government to make the future utilization of construction robots more feasible.
- Construction robots could be used to replace low-level, high-risk jobs in the future.
- It is unknown whether intelligent robots can replace a large number of workers in the future. Nevertheless, if so, it will result in unemployment for many workers and impose additional burdens on the government.

[insert Fig. 8 here]

5 Scenario Transfer

The developed scenarios have revealed that the future alternatives of construction robots for building in Hong Kong are strongly coupled with the sociotechnical environment and developments. This section covers the Scenario Transfer phase, in which disruptive events are further analyzed, and strategies to enable scenario transfer and move the industry forward are elaborated, with references to relevant studies or cases.

5.1 Analyze disruptive events

Possible disruptive events that could interfere with the future development of construction robots are identified through a historical review of the development of construction robotics. Starting from the late 1970s, the Japanese have surpassed the progress of other regions of the world in the area of construction robots with extensive R&D activities. However, its economic crisis in the 1990s sharply slowed down technological advancement and restrained robotic applications [7]. In this context, economic turmoil associated with social instability is a possible disruptive event, which may force the implementation of construction robots toward Scenario 1, and strongly deaccelerate or disrupt Scenarios 3 and 4. Strengthening collaboration and communication on R&D for robots can help to reduce the negative impacts of such an event. Another possible disruptive activity interfering with the use of construction robots would be the softened regulatory control on cheap foreign construction workers that diminish the allure of robots to solve labor issues. All scenarios will be affected, but rapid technological progress to improve the economic effectiveness of robotics will erode whatever cost advantage the imported labor enjoys.

5.2 Elaborate strategies

5.2.1 Identification of driving forces, opportunities, and challenges

The developed scenarios highlight how the utilization of construction robots may change in Hong Kong in the coming decades, where opportunities and challenges co-exist. The driving forces of each scenario should first be identified to determine appropriate strategies that maximize the opportunities and minimize potential risks. Considering their influence on other factors and their distinctiveness in different scenarios, driving forces could be represented by KIFs. These KIFs were found to be extremely influential in the factor analysis in Section 4.2 and are the main causes of variations among scenarios. Seven KIFs were defined and further classified as primary (i.e., initial investment cost and economic performance associated with robots, ease of use of robots, availability of robotic technology, and culture of innovation in the industry) and secondary (i.e., the scale of prefabrication, government support of robotics applications in construction, and work structure and organization) based on whether they are “uncontrollable” or “controllable” by regulators and industry [9]. Opportunities and challenges can be identified from the corresponding outcomes of those significantly affected KIFs and other IFs under the scenarios.

Table 4 provides a detailed scenario-based description of driving forces, and the identified opportunities and challenges facing the industry. Technologically, Scenario 1 offers chances for robotics startups to be the technology pioneers and leaders, along with high risks of being frustrated by indifferent market; Scenario 2 and 3 provide golden opportunities for construction robotics, under the “survival of the fittest” pressure from the industry practices; Scenario 4 creates the stage for disruptive construction robotics to takeoff, albeit challenged by a highly competitive market.

[insert Table 4 here]

5.2.2 Recommended strategies for stakeholders

Based on Table 4, policies can be proposed for all stakeholders along the value chain, including industry (also conventional construction companies and emerging companies for construction robots), government (its departments and agencies), and academia in Hong Kong. The analysis should work backward from the implications of the four scenarios and their impacts on the current situation. For industry practitioners, they should fully seize technological opportunities by integrating different scenarios into their technology strategy and business plans. For government and academia, strategic recommendations should focus on how to realize desirable scenarios for a flourishing future and to mitigate undesirable outcomes. Primary driving forces imply the technological uncertainties can alter utilization behavior, which are uncontrollable, but trends can be learned by decision-makers and the government to make correct scenario prognoses and corresponding strategic plans. Accordingly, strategic repertoires for each scenario are explored where the undergoing trajectory is most likely to arrive.

Scenario 1 (Bottleneck) is, in general, an unexpected scenario. Although substantial employment opportunities are provided in this scenario, the industry is slowly moving forward. The escalation of construction costs will continuously lead to increasing property prices and rentals, causing severe livelihood and other social problems. Therefore, the following strategies and measures are proposed to prevent the occurrence of the scenario or change its development trajectory.

- *Upgrading existing machinery and equipment.* The conservative culture of the industry could inhibit robotics development and maintain the dominance of traditional trades. To overcome severe labor challenges and boost productivity, the gradual upgrading of existing machinery and equipment toward automation and intelligence [e.g., 59] should be fostered in the whole industry.
- *Emphasizing technology usability and interoperability*. Robotics startups should work closely with the industry and develop real-world cases with proven benefits to raise industry awareness and improve technology usability. A later step should be the focus on robot-oriented design [24] to guide and enable the applicability, simplicity and efficiency of robots in real-world practice.
- *Providing a fertile environment for construction innovation*. The government should create a productive environment for construction innovation by providing funding support and incentives to construction companies and academia for developing and deploying promising technological innovations, including construction robotics. This could further foster the culture of innovation in the industry.

- *Strengthening talent cultivation and labor management*. The government and academia should provide sufficient education and training on the latest innovations in the construction industry. Traditional contractors, especially specialized subcontractors, should put more effort into labor training and labor resource management. The entire industry should work together toward safer and healthier construction sites to attract the young generation.

Scenario 2 (Age of Iron Worker) is a transitional stage for the industry toward the direction of a better-equipped workforce. The technological, economic and cultural issues, to a certain extent, restrict the utilization of more disruptive construction robots in Hong Kong. Problem-solving, combined with the rational use of robots, should focus on the following strategies.

- *Promoting diversified innovations*. The government should capitalize on advancements in diversified innovations, including robots and other emerging techniques, and vigorously promote their real-world adoption to tackle challenges of stagnant productivity, high construction cost and housing affordability. Accordingly, the partnership between the industry and universities should be encouraged, financial and non-financial support should be provided, and enhanced education and pertinent training programs should be established.
- *Grasping technological opportunities of construction robots.* Construction companies should explore investment opportunities in construction robotics in the global arena and evaluate potential technologies within the local market to allocate their R&D resources and efforts accordingly. The emphasis should be on robot-oriented design and development [24] to promote the application of construction robots. It is recommended for the industry to first focus on more affordable wearable robotics or

assistant robotics that are well developed in other industries (e.g., [15, 16]), and pay attention to those trades facing severe labor problems.

- *Promoting inter- and intra-industry collaborations*. The industry, as a whole, should consolidate their inter- and intra-industry communication and cooperation on robotic application-oriented research, technology transfer, and real-world trials and develop new business models under the sharing economy [28] to share the benefits and risks associated with robotic implementation.
- *Alleviating labor shortage via a multipronged approach*. The government should adopt a multipronged approach to solve aging labor and shortage issues [1] regarding supporting technological research on labor-saving, promoting education and training, improving welfare policy for construction workers, strengthening recruitment informatization, etc.

Compared to Scenarios 1 and 2, Scenario 3 (Dynamic Co-evolution of Robotization and Modularization) demonstrates an innovation-based industry with diversified advancements, led by robotization and modularization. Strategic plans should be formulated to promote technological mutualism or symbiosis [37] to maximize the benefits, as well as address potential labor surplus caused by the large-scale use of off-site construction and on-site automation.

- *Grasping multiple technological opportunities.* Construction companies should evaluate the opportunities under new construction methods and technologies, and upgrade their practices, operational processes, or business models accordingly. Companies for construction robots should seek to explore business opportunities regarding the interoperability and compatibility of robots in construction sites via increasing prefabrication [36] and modularization [37].

- *Transmitting project-based knowledge and experience.* Project-based knowledge and experience regarding different robots and modularization (or increasing prefabrication) should be learned and transferred industrial-wide. The government and academia should investigate the merits and drawbacks of technology applications within the context of projects, and establish technical guidance for the industry to take optimized technological solutions.
- *Promoting technological mutualism and integration.* More cross-disciplinary research should be encouraged toward robotics and modularization as well as other innovations through specialized R&D institutions, to facilitate mutualism and integration of robotics and off-site technologies, and to promote benign competition [37]. The government should improve its approval process for building projects to reduce the institutional barriers for adopting innovative construction technologies.
- *Eliminating labor surplus issues*. The government and academia should set up effective training and skills programs to push construction workers into new skills and career areas of modular construction and robotics training.

Scenario 4 (Rise of the Robots) seems to be the most promising configuration to unleash the power of construction robots for a productive industry. Robotic technologies are utilized vastly more effective and fruitful through advances in sensor technology, materials, and AI, forming a fiercely competitive market. Meanwhile, the rise of robots could significantly reduce labor demand and potentially result in a high industry unemployment rate. The following strategies are thereby proposed.

- *Strengthening the competitiveness of construction companies*. Construction companies should keep pace with worldwide technological innovations for construction robots to avoid being technological laggards and losing competitiveness in the market. Small construction companies should emphasize the development of originality and creativity, either in technology or soft aspects.

- *Emphasizing the wider benefits of technology.* The government should promote the use of robots for a sustainable transition and formulate standards to evaluate the sustainability of robotic technologies in projects [12, 17, 60].
- *Eliminating labor surplus issues*. The government and academia should establish training programs to advance the skillsets of construction workers, develop new career areas emerging from construction robotics, and continuously nurture traditional talents for irreplaceable construction tasks to fit the new industry. The government should also provide adequate support to encourage career changes of traditional construction workers to other sectors.

Although the focus of strategies is different for each scenario, the crucial role of workers is highlighted in the future utilization of construction robots. Construction robots are expected to solve severe labor issues, while also generating physical, ethical, legal and social issues in human-robot collaboration [17]. Besides, the transition and development of staff to be more open-minded and knowledgeable [28] is essential for strategic planning of all scenarios.

6 Discussions

In the present study, the authors have, for the first time, applied a systematic scenario projection approach in the field of construction robotics. Hence, they made an initial step toward the application of a key tool for the future comprehensive development and systems engineering of construction robots, by enabling industries to structure the solution space, and thus mitigate uncertainties in the requirements engineering and management process. The development of construction robots should start now in preparation of a largely unknown future. Starting with the use of the Hong Kong construction industry as an initial test case, the findings of our study are generalized toward and classified into three categories: theoretical dimension, methodological dimension, and practical dimension.

- *Theoretical dimension*: Applying the multidimensional, multilevel systems perspective, this study makes a theoretical contribution to the field of construction robots by comprehensively illustrating how utilization can be shaped in sociotechnical contexts. Dubois and Gadde [61] argued that innovation often suffers in the construction industry as a loosely coupled system. For construction robots, the dialectics [30] of couplings should be emphasized in terms of technology-oriented cooperation patterns and other technology alternatives.
- *Methodological dimension*: The study demonstrates and verifies the scenario approach as a scholarly research methodology [10], as well as the need for a combination of interdisciplinary emphasis and scenario exploration methods [42]. In this study, the fuzzy theory and DEMATEL method were integrated in the KIF exploration step in the scenario approach, which addresses the ambiguous issues in judgment-based factor analysis, and enables a contextual understanding of the scenarios. The scenario approach serves as the initial steps toward a novel tool in the context of systems engineering for the future requirements definition and specification of construction robots. The whole methodology can also be applied in other foreseen studies for technology development and utilization.
- *Practical dimension*: Practically, this study tested the approach with the Hong Kong case to understand the future of construction robots and their impacts on the building

industry (solution space) from evidence-based analysis. The findings enable stakeholders to fully seize the technological opportunities and systematically shed light on the potential risks, uncertainties, and design factors and inputs. The study supplements existing studies [7, 13, 28] by offering a multiplicity of possible future scenarios and targeting the specific technological application of construction robots. In particular, policy and decisions have been proposed for the adjustment of the identified “controllable” driving forces to modify or adapt the development of the identified “uncontrollable” driving forces, thus steering the utilization and development of construction robots toward the desired direction. In this respect, technical features and industrial culture are key to the future utilization of construction robots, whilst the government could exert a multifaceted influence to foster favorable utilization. More specifically, the findings also echo previous literature in emphasizing the importance of technology interaction/compatibility explorations [35] and worker-oriented studies [15, 28] of construction robots. The application of the developed scenario approach to Hong Kong as a representative test case has demonstrated that this new tool can deepen the understanding of and structure the dynamic contexts (robot ecosystem) around potential technological development targets. Regarding the applicability of the tool for other economies, the differences in KIFs and their projections could result in different scenarios and associated strategies.

Despite the theoretical, methodological, and practical contributions, limitations were also identified in this study. Firstly, the combination and reduction of initially identified IFs might affect the integrity and correlation of factors, which could lead to the neglect of some essential elements in the following analyses. Secondly, consistency evaluation of projections was conducted by the scenario team, which is inevitably subjective and could influence the outcome of the scenarios. Thirdly, the accuracy of assumptions made during the whole approach is not sufficiently assured, although the integration of fuzzy logic theory improved the reliability of judgments in KIF identification. Hence, future improvement of the integrated scenario approach for more robust technological forecasting is expected.

7 Conclusions

The lack of systematic approaches to explore future scenarios and solution spaces has become a major challenge in the conception and systems engineering process in construction robot development. Therefore, the research presented in this paper attempts to take the first step toward the development of a new tool for the construction robotics field that can inform and support actual requirements management and systems engineering processes by scenario-based analysis. The Hong Kong construction industry was used as an initial test case. In this context, plausible scenarios for the utilization of construction robots for buildings (in Hong Kong) for the year 2035, i.e., “Bottleneck,” “Age of Iron Worker,” “Dynamic co-evolution of Robotization and Modularization,” and “Rise of the Robots,” were systematically generated based on the integrated scenario approach while considering the input and perspectives of professionals from both academia and industry. The findings demonstrate that the future use of construction robots is strongly associated with technological and social developments within the economic and political ecosystem in the industry. “Uncontrollable” and “controllable” driving forces, as well as opportunities and challenges under each scenario, were further identified. Strategies for different stakeholders were explored to adjust the “controllable” forces to modify or adapt the development of “uncontrollable” forces affecting the utilization of construction robots, in an attempt to maximize the potential opportunities and mitigate the risks for the future prosperity of the industry. The crucial role of workers is highlighted in managing and strategizing the future use of construction robots for all scenarios. The study also has implications for the technical potential of different types of construction robots; hence, it can serve as a valuable guide for the construction industry's comprehensive development roadmap and prospects.

Future research will extend and further validate the integrated scenario approach applied in this study as a novel tool for structuring the context of construction robot development as part of the fundamentals of a systems engineering process for construction robots. The findings presented in this paper can be expanded and integrated into technology road-mapping techniques (e.g., [37]) and comprehensive systems engineering models (e.g., [26]) to conduct a fully integrated engineering effort [26] for construction robot development.

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Appendix A. The modified fuzzy DEMATEL method

Considering the paper length, the detailed numerical analysis based on the modified fuzzy DEMATEL method is not covered. The main steps in the modified fuzzy DEMATEL method for KIF identification are as follows.

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. According to Chen and Hwang [62], 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 A.1.

[insert Table A.1 here]

2. Defuzzifying 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 a_{ij}^k, which can be performed according to Converting Fuzzy data into Crisp Scores (CFCS) method [63] as follows.

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

$$l_{ij}'^k = (l_{ij}^k - \min_{1\le k\le K} l_{ij}^k) / (\max_{1\le k\le K} r_{ij}^k - \min_{1\le k\le K} l_{ij}^k) \tag{1}$$

$$m_{ij}'^k = (m_{ij}^k - \min_{1\le k\le K} l_{ij}^k) / (\max_{1\le k\le K} r_{ij}^k - \min_{1\le k\le K} l_{ij}^k) \tag{2}$$

$$r_{ij}'^k = (r_{ij}^k - \min_{1\le k\le K} l_{ij}^k) / (\max_{1\le k\le K} r_{ij}^k - \min_{1\le k\le K} l_{ij}^k) \tag{3}$$

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

$$ls_{ij}^k = m_{ij}'^k / (1 + m_{ij}'^k - l_{ij}'^k) \tag{4}$$

$$rs_{ij}^k = r_{ij}'^k / (1 + r_{ij}'^k - m_{ij}'^k) \tag{5}$$

Thirdly, the total normalized value *nx* can be computed as:

$$nx_{ij}^{k} = [ls_{ij}^{k}(1-ls_{ij}^{k}) + rs_{ij}^{k} \times rs_{ij}^{k}]/(1-ls_{ij}^{k}+rs_{ij}^{k}) \tag{6}$$

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

$$a_{ij}^{k} = \min_{1\le k\le K} l_{ij}^{k} + nx_{ij}^{k}(\max_{1\le k\le K} r_{ij}^{k} - \min_{1\le k\le K} l_{ij}^{k}) \tag{7}$$

3. Normalizing and generating the average matrix. Based on the above defuzzification, the new initial influence matrix of the professional *k* is obtained as $A_k = [a_{ij}^{k}]_{n\times n}$. Here, the added normalization step is applied to obtain the normalized initial influence matrix $D_k = [d_{ij}^{k}]_{n\times n}$, which is the mapping from d_{ij}^{k} to [0, 1]. The commonly used method [49, 50] is adopted for the normalization as follows.

$$D_k = s_k A_k \tag{8}$$

where

$$s_k = \frac{1}{\max\limits_{1\le i\le n} \sum_{j=1}^{n} a_{ij}^{k}} \tag{9}$$

Then, the average matrix *A* can be obtained, with the element $a_{ij}(1\le i, j\le n)$ calculated as:

$$a_{ij} = \frac{1}{K}\sum_{k=1}^{K} d_{ij}^{k} \tag{10}$$

4. Calculating the normalized direct and indirect influence matrix. The average matrix *A* can be normalized via equations (10) and (11) to calculate the normalized direct influence matrix *D*. Similar to obtaining the transition matrix of a Markov chain, the normalized indirect influence matrix *ID* can be computed from the normalized direct influence matrix *D*.

$$ID = D^2 + D^3 + \ldots + D^\infty = \sum_{h=2}^{\infty} D^h = D^2 \left(1 - D\right)^{-1} \tag{11}$$

where I denotes the identity matrix.

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

$$T = D + ID = \left[D\left(1 - D\right) + D^2 \right]\left(I - D\right)^{-1} = D\left(I - D\right)^{-1} \tag{12}$$

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:

$$r_i = \sum_{j=1}^{n} t_{ij} \tag{13}$$

$$c_j = \sum_{i=1}^{n} t_{ij} \tag{14}$$

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 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 categorize factors into cause and effect groups [50]. 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 [49] can then be obtained by mapping the dataset of ($r+c$, r-c), which visualizes the complex causal relationships among factors. Key factors can thereby be identified regarding the importance and causality of the influence.

Appendix B. DEMATEL questionnaire in KIF identification

[insert Fig. B.1 here]

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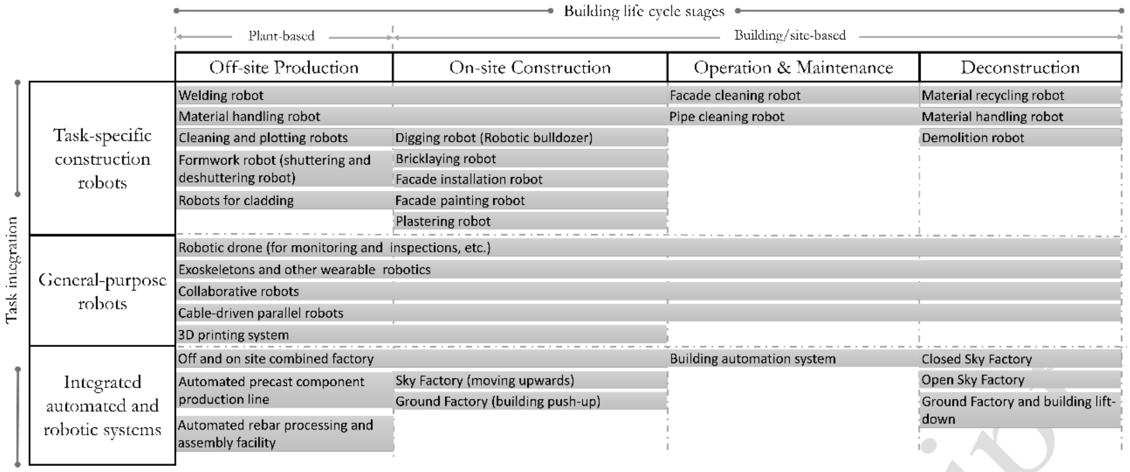


Fig. 1. Classification of construction robots for buildings.

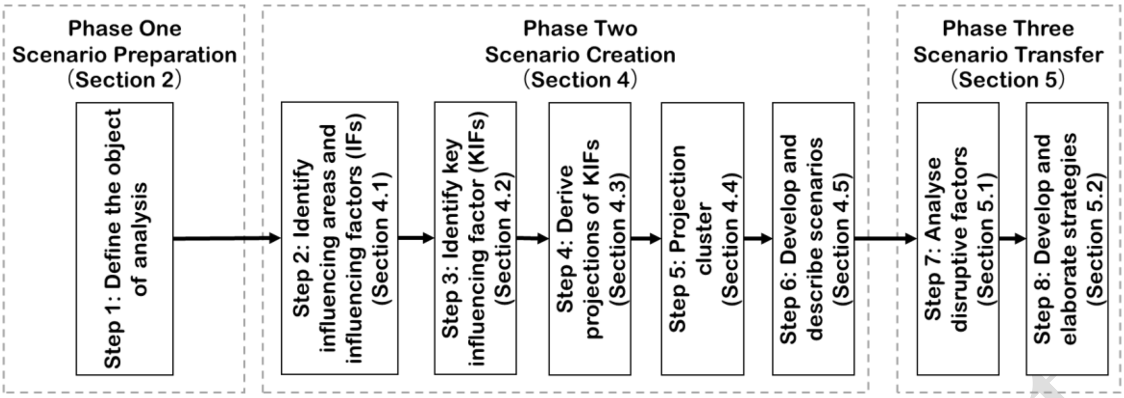
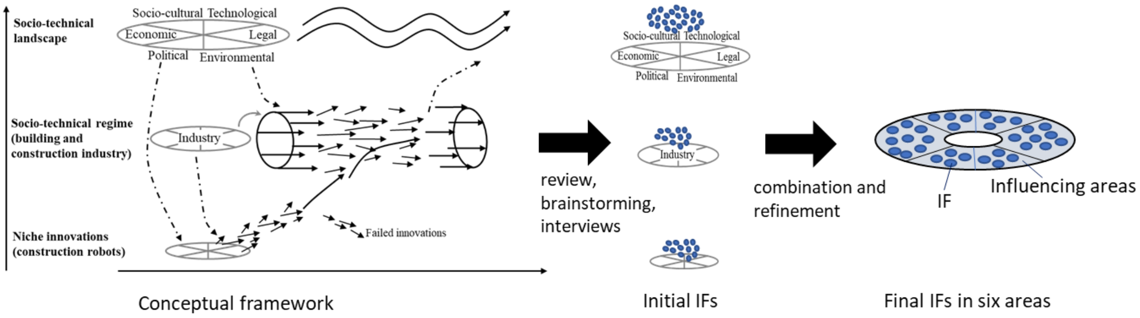
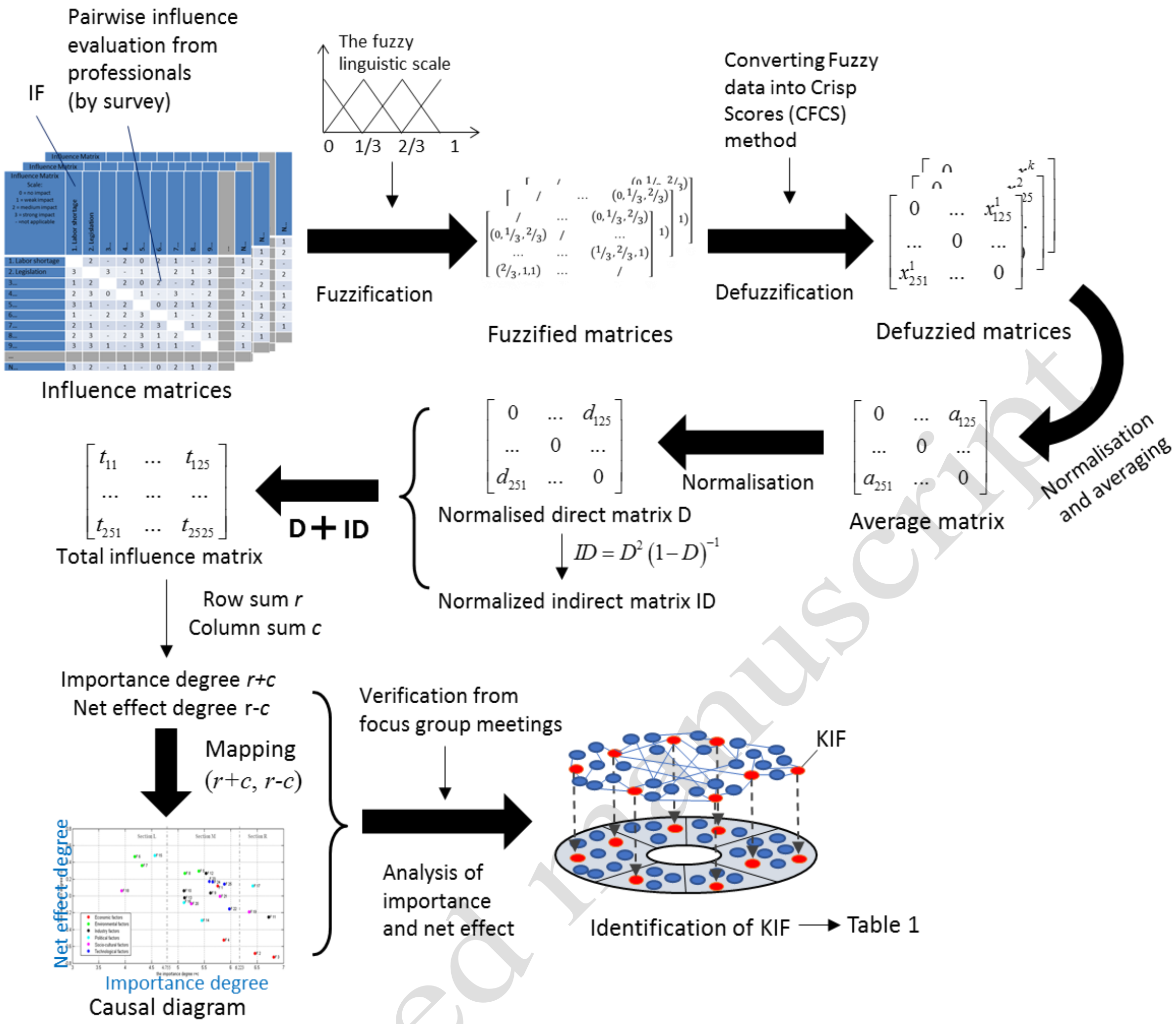


Fig. 2. Overview of the integrated scenario approach.

1055 

1056 **Fig. 3.** Process of the identification of influencing areas and influencing factors.



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1058 **Fig. 4.** Process of key influencing factors identification based on a proposed modified

1059 fuzzy DEMATEL.

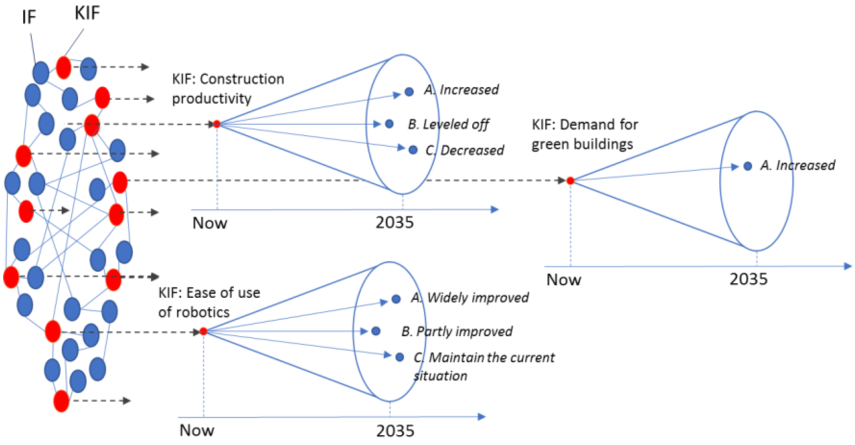


Fig. 5. Process of the development of key influencing factor projections.

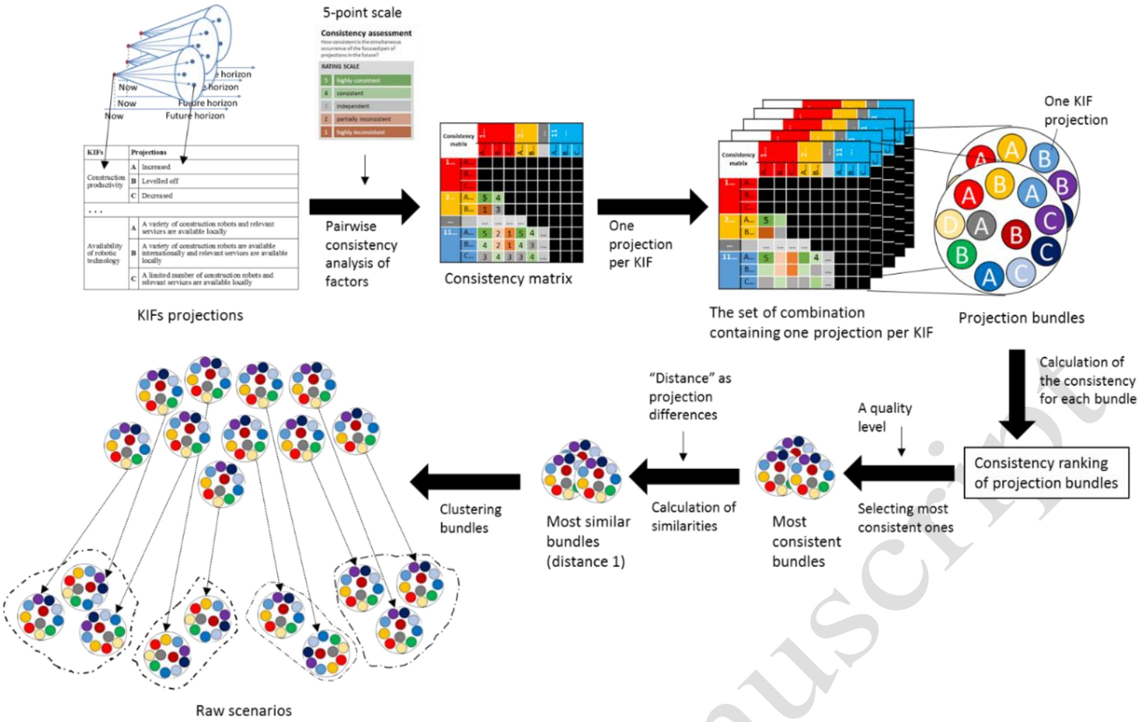
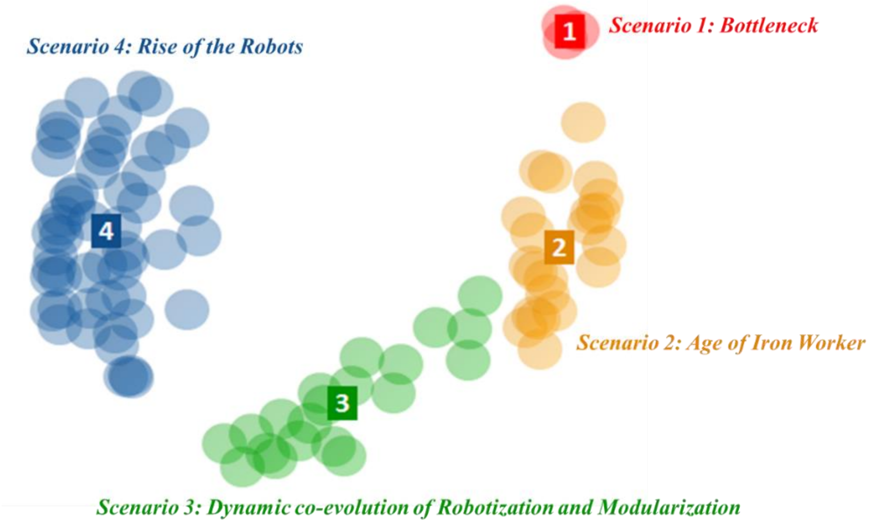


Fig. 6. Process of clustering projections to create raw scenarios.



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1065 **Fig. 7.** Spatial relationships and clustering of projection bundles into raw scenarios.

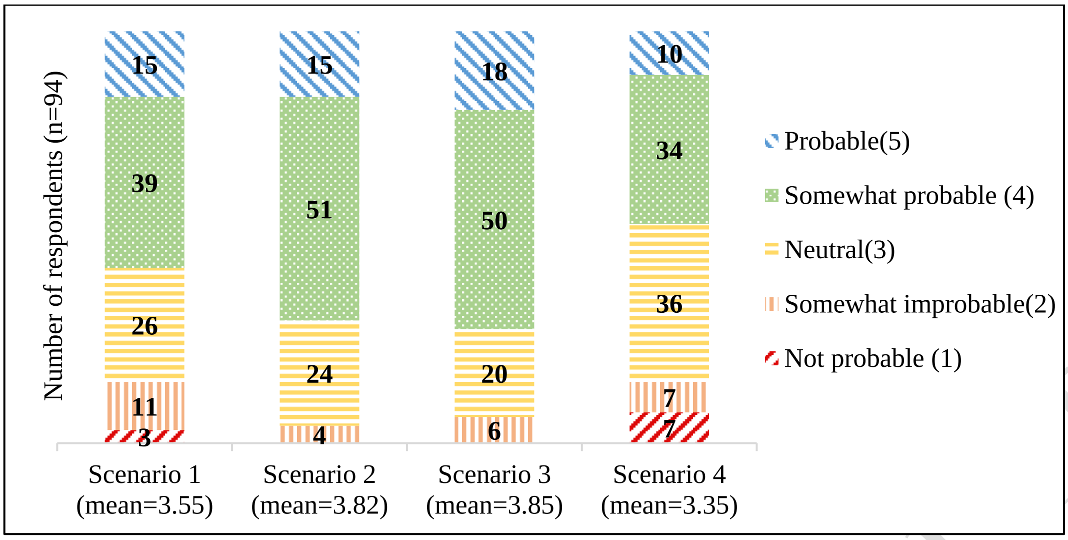
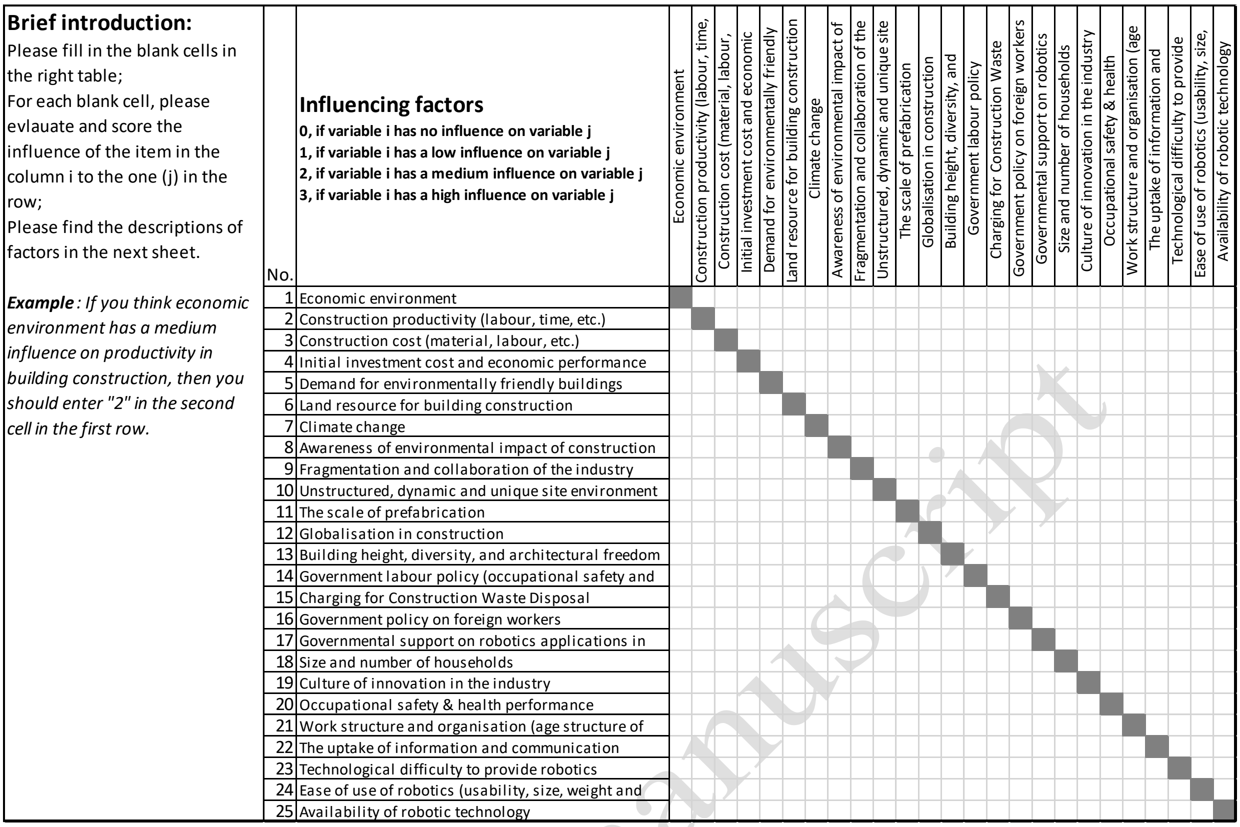


Fig. 8. Appraisal of the probability of the four developed scenarios by contractors.



Brief introduction:
Please fill in the blank cells in the right table;
For each blank cell, please evlauate and score the influence of the item in the column i to the one (j) in the row;
Please find the descriptions of factors in the next sheet.

***Example**: If you think economic environment has a medium influence on productivity in building construction, then you should enter "2" in the second cell in the first row.*

Influencing factors
0, if variable i has no influence on variable j
1, if variable i has a low influence on variable j
2, if variable i has a medium influence on variable j
3, if variable i has a high influence on variable j

No.		Economic environment	Construction productivity (labour, time,	Construction cost (material, labour,	Initial investment cost and economic	Demand for environmentally friendly	Land resource for building construction	Climate change	Awareness of environmental impact of	Fragmentation and collaboration of the	Unstructured, dynamic and unique site	The scale of prefabrication	Globalisation in construction	Building height, diversity, and	Government labour policy	Charging for Construction Waste	Government policy on foreign workers	Governmental support on robotics	Size and number of households	Culture of innovation in the industry	Occupational safety & health	Work structure and organisation (age	The uptake of information and	Technological difficulty to provide	Ease of use of robotics (usability, size,	Availability of robotic technology
1	Economic environment	■																								
2	Construction productivity (labour, time, etc.)		■																							
3	Construction cost (material, labour, etc.)			■																						
4	Initial investment cost and economic performance				■																					
5	Demand for environmentally friendly buildings					■																				
6	Land resource for building construction						■																			
7	Climate change							■																		
8	Awareness of environmental impact of construction								■																	
9	Fragmentation and collaboration of the industry									■																
10	Unstructured, dynamic and unique site environment										■															
11	The scale of prefabrication											■														
12	Globalisation in construction												■													
13	Building height, diversity, and architectural freedom													■												
14	Government labour policy (occupational safety and														■											
15	Charging for Construction Waste Disposal															■										
16	Government policy on foreign workers																■									
17	Governmental support on robotics applications in																	■								
18	Size and number of households																		■							
19	Culture of innovation in the industry																			■						
20	Occupational safety & health performance																				■					
21	Work structure and organisation (age structure of																					■				
22	The uptake of information and communication																						■			
23	Technological difficulty to provide robotics																							■		
24	Ease of use of robotics (usability, size, weight and																								■	
25	Availability of robotic technology																									■

Fig. B.1. Template for questionnaire survey in KIF identification.

Table 1. Details of the participants in interviews, surveys and focus group meetings.

Item	**Descriptions**	*Step 2*	*Step 3*	*Step 3&4*	*Step 7*	**Total**
		I*	QD	F	QS	
Primary area of practice (professional)	Contractor (main and sub)	7	4	2	94	107
	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	6-9	3	7	4	6	20
	10-19	7	9	6	20	42
	More than 20 years	10	2	6	68	86
Total		20	18	16	94	148

*I=interviews; QD=DEMATEL questionnaire survey; F=focus group meeting; QS=Scenario evaluation questionnaire survey.

Table 2. Identified KIFs and their descriptors.

Influence areas	**KIF**	**Descriptors**
Economic	Construction productivity	The amount of floor area completed per man day
	Construction cost (material, labor, etc.)	Construction cost index
	Initial investment cost and economic performance associated with robots	Initial investment cost and payback period
Environmental	Demand for environmental friendly buildings	Demand for green buildings
Industry	The scale of prefabrication	Percentage by volume (prefabrication ratio) and use
Political	Governmental support on robotics applications in construction	Financial support, guidance, public procurement, legal issues for robots
Socio-cultural	Culture of innovation in the industry	Mindset and R&D activities
	Work structure and organization	Age structure of the workforce, shortage of skilled labor, education and training
Technological	The uptake of information and communication technology (ICT)	The uptake of Building and Information Modeling (BIM), Internet of Things (IoT), etc.
	Ease of use of robots	Usability, size, weight, and power supply, etc.
	Availability of robotic technology	Availability of construction robots and relevant services

1075 **Table 3.** Final list of KIFs projections.

KIFs	**Projections**	
Construction productivity	**A**	Increased
	B	Leveled off
	C	Decreased
Construction cost (material, labor, etc.)	**A**	Construction cost Indices are expected to level off
	B	Construction cost Indices are expected to increase about 50%
	C	Construction cost Indices are expected to increase about 100%
	D	Construction cost Indices are expected to increase about 200% or even more
Initial investment cost and economic performance associated with robots	**A**	Initial investment cost has decreased, payback period less than 2 years
	B	Initial investment cost has decreased, payback period more than 2 years
	C	Initial investment cost remains the same, payback period less than 2 years
	D	Initial investment cost remains the same, payback period more than 2 years
Demand for environmental-friendly buildings	**A**	Increased
The scale of prefabrication	**A**	Increased prefabrication ratio, with the increased use of prefabrication method in the private sector
	B	Increased prefabrication ratio, with still limited use of prefabrication method in the private sector
	C	Prefabrication ratio remains the same, with the increased use of prefabrication method in the private sector
Governmental support on robotics applications in construction	**A**	More financial support and incentive scheme in robotics research and applications in construction, and guidance and standards are developed
	B	Financial support in construction robotics remains the same, and the government promote the use in public projects
	C	Tighten the financial support in construction robotics and focus more on other new technologies
Culture of innovation in the industry	**A**	Positive mindset on robotics by the industry and increased R&D expenditure
	B	Positive mindset on robotics by the management, but reluctant by the workers
Work structure and organization	**A**	The industry is suffering a serious skilled labor shortage and aging issue. The quality of education and training remain similar.
	B	The industry is suffering a serious skilled labor shortage and aging issue. Improved education and training are provided.
	C	The industry is suffering a moderate skilled labor shortage but with a younger age structure. Improved education and training are provided.

The uptake of information and communication technology (ICT)	**A**	Increased
Ease of use of robots	**A**	Widely improved
	B	Partly improved
	C	Maintain the current situation
Availability of robotic technology	**A**	A variety of construction robots and relevant services are available locally
	B	A variety of construction robots are available internationally and relevant services are available locally
	C	A limited number of construction robots and relevant services are available locally

1077 **Table 4.** Driving forces, opportunities, and challenges under each scenario.

	Scenario 1: Bottleneck	**Scenario 2: Age of Iron Worker**	**Scenario 3: Dynamic Co-evolution of Robotization and Modularization**	**Scenario 4: Rise of the Robots**
Primary driving forces (uncontrollable KIFs)	• High initial investment of construction robots • Long payback period of construction robots • Not well-developed robotics usability • Reluctance on robotics	• Justified economic performance of certain construction robots • Partly improved robotics usability • Reluctance on radical changes by robotics	• Justified economic performance of certain construction robots • Partly improved robotics usability • Positive mindset on robotics	• Decreased initial investment of construction robots in general • Short payback period of construction robots in general • Widely improved robotics usability • Positive mindset on robotics
Secondary driving forces (controllable KIFs)	• Tightened governmental financial support in construction robotics • Insufficient education and training	• Promotion of construction robots in government procurements	• Increased use of modularization and prefabrication method • Improved education and training	• More governmental financial support and incentive schemes • Well-developed guidance and standards • Improved education and training
Opportunities	• Increased employment opportunities	• Improved occupational health and safety	• Increased productivity • Controlled construction cost • Improved occupational health and safety • Improved sustainability	• Increased productivity • Controlled construction cost • Improved occupational health and safety • Improved sustainability • Improved labor quality
Challenges	• Low productivity • High construction cost • Aging workforce • Skilled labor shortage	• Stagnant productivity • High construction cost • Aging workforce	• Fierce technological competition • Increased unemployment rate (labor surplus)	• Increased unemployment rate (labor surplus)

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Table A.1. 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)