Exploring the interactions among factors impeding the diffusion of prefabricated building technologies: Fuzzy Cognitive Maps

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Abstract

Purpose

This study aims to identify the interactions of factors impacting the widespread adoption of prefabricated building technologies and the intervention strategies to facilitate the development of prefabrication based on Fuzzy Cognitive Maps (FCMs).

Design/methodology/approach

Through in-depth interviews with six stakeholder groups, namely the government, developers, designers, contractors, manufacturers and researchers, thirteen critical factors were identified and used to construct stakeholder-grouped FCMs, which were further aggregated into a collective FCM. The complexity and density of the collective FCM, and the centrality of factors in the FCM were examined. Subsequently, a series of "what-if" simulations of the collective FCM were conducted to analyze the effectiveness of different interventions in promoting prefabrication.

Findings

The results show that three factors including market demand, cost, and policies and regulations have been mentioned by all stakeholder groups. However, these factors were ranked differently by stakeholder groups, implying that different stakeholder groups perceive the barriers to prefabricated building technologies differently. FCM simulations show that strengthening policies and regulations yield the strongest overall effect stimulating prefabrication, alleviating the organizational and environmental barriers more than the technological barriers, while improving the knowledge and expertise alleviate the technological barriers more. These measures need to be accompanied by other approaches, such as reducing cost and improving quality.

Research and practical implications

It is a tough task to promote prefabrication as it is affected by numerous barriers with complex interactions, which have been overlooked by previous studies. This study clearly shows which strategy could tackle which barriers to prefabrication through the FCM simulations. This provides valuable references for the enterprises' decision making and the governments' policymaking to facilitate the diffusion of prefabricated building technologies.

Originality/value

Few studies aim to analyze the interactions among the barriers to prefabrication, while this study specifically investigates this issue by illustrating the complex interactions using Fuzzy Cognitive Maps (FCMs). Few studies also aim to identify the intervention strategies promoting prefabrication based on a quantitative approach, while this study employs FCM simulations to directly simulate the effectiveness of different strategies to facilitate prefabrication in a quantitative manner.

Keywords: Approach, simulation, technology, innovation, construction.

Introduction

Buildings worldwide account for more than 40% of the global carbon dioxide (CO_2) emissions and generate various environmental impacts (Darko et al., 2017; Pons & Wadel, 2011; Zhou et al., 2017). Prefabricated building technologies, where a significant amount of building components is manufactured in a controlled offsite environment before being transported to site for efficient assembly, have been proposed as a sustainable alternative to conventional onsite construction (Gan et al., 2018a; Zhang et al., 2014). Since the building process is improved by mechanization and automation, it is easier to reuse and recycle building materials (Pons et al., 2011), especially when modular components are involved. Consequently, significant benefits have been observed including productivity improvement, cost reduction, less construction waste, less emissions, reduction of energy and water consumption, less labour demand and better safety (Chen et al., 2010; Kamali & Hewage, 2017; Mao et al., 2015; Pan et al., 2012; Polat, 2008; Zhong & Wu, 2015).

However, prefabricated building technologies are still not widely adopted. Multiple studies have been conducted to explore the factors impeding the diffusion of prefabricated building technologies by using various methods such as exploratory factor analysis, importance index, fuzzy set theory, etc (Lovell & Smith, 2010; Mao et al., 2015; Pan et al., 2012; Polat, 2010; Rahman, 2014). Although a range of barriers to its implementation has been identified, limited studies have explored the interactions between those barriers. Construction innovation is embedded in industry networks involving many interconnected elements (Chang et al., 2015; Winch, 1998). The factors impeding the diffusion of prefabricated building technology are interrelated, generating a complex system which is hard to be studied due to the difficulty in measuring the interactions among those factors quantitatively (Rajaram & Das, 2010). Meanwhile, the uptake of construction innovation requires the involvement of various stakeholders, whose behavior is influenced by their perceptions of these barriers (Vanwindekens et al., 2013; Xue et al., 2017). Few studies investigated how various groups of stakeholders perceive the interrelationships among the barriers to prefabrication.

One quantitative model that is able to investigate the interactions among factors is Fuzzy Cognitive Map (FCM). FCM has been successfully applied in various areas, such as agriculture, environment and energy (Kyriakarakos et al., 2014; Lopolito et al., 2011; Zhang et al., 2013). However, the application of FCM to the diffusion of construction innovations is very limited. This study utilizes FCM to explore factors impacting the diffusion of prefabricated building technologies with three objectives: (1) to identify the barriers to the diffusion of prefabricated building technologies based on interviews with various stakeholders,

(2) to identify the interactions among those factors by using FCM and (3) to simulate how the interrelated factors impact each other dynamically, so that the effectiveness of different interventions to facilitate prefabrication could be revealed. By identifying and simulating the interrelated factors impacting prefabrication, this study can facilitate effective and efficient policy-making and decision-making for promoting prefabricated building technologies in the future.

Literature analysis

Due to the unique industrial characteristics, such as one-of-a-kind nature, site production, and temporary organization, the construction industry is well known for its low level of innovation (Chang et al., 2016; Chang & Lu, 2017b). The diffusion of prefabricated building technologies remains slower than anticipated (Gan et al., 2018b; Xue et al., 2017). Several studies have explored the factors impeding the diffusion of prefabricated building technologies. With reference to the TOE (Technology-Organization-Environment) framework which has been extensively adopted in the research field of construction innovation (Wei et al., 2015; Xue et al., 2017), barriers to prefabrication can be categorized into three categories, namely technological factors, organizational factors and environmental factors.

The technological factors impacting prefabrication refer to the disadvantages of prefabricated building technologies comparing with the conventional construction approach. Higher cost has been regarded as a factor significantly impeding the diffusion of prefabrication (Mao et al., 2016). Besides, poor quality (Kamali et al., 2017), the monotonous appearance (Zhai et al., 2014), and the constraints of logistics (Polat, 2008) also impede the adoption of prefabricated building technologies. The organizational factors explain the organizational constraints hindering the adoption of prefabrication by construction firms. The traditional project process and business models have been argued prohibiting the use of prefabrication (Nadim & Goulding, 2011; Zhang et al., 2014). The lack of knowledge and expertise also constrains the use of prefabrication (Polat, 2008, 2010). The poor design and manufacturing capacity of manufactures has also been highlighted as important organizational barriers (Gan et al., 2018b). The environmental factors emphasize the context where a firm conducts its business. The lack of social acceptance and limited market demand present a significant challenge for the diffusion of prefabrication (Mao et al., 2015; Nadim et al., 2011; Zhai et al., 2014). The lack of codes and standards, as well as inadequate supporting policies and regulations could also result in the difficulty in adopting prefabrication (Gan et al., 2018b; Zhai et al., 2014; Zhang et al., 2014).

Although these previous studies identified some factors impacting prefabricated building technologies, there is a significant gap of knowledge. Most previous studies use statistical methods to propose importance rankings of the factors impacting prefabrication, and the policy suggestions are proposed mostly in a subjective manner based on these rankings (Gan et al., 2018b). However, this approach neglects the complex interactions among the factors. Some factors may not be rated with high importance, but could have various linkages with other factors, and thus become central in promoting prefabrication. Ideally, the effectiveness of different strategies to facilitate prefabrication need to be quantitatively simulated considering the complex interactions among the factors impacting prefabrication, rather than subjectively assumed based on the isolated importance rankings of the impacting factors. Actually, most previous studies focus on identifying the various factors impacting prefabrication, while the interactions among these factors seem neglected.

By specifically responding to this gap of knowledge using FCM, this study aims to provide important implications theoretically, methodologically and practically. Theoretically, few studies aim to analyze the interactions among the barriers to prefabrication, while this study aims to specifically investigate this issue. Methodologically, this study employs FCM simulations with the aim to directly simulate the effectiveness of different strategies to facilitate prefabrication in a quantitative manner. Practically, this study aims at clearly showing which strategy could tackle which barrier to prefabrication through the FCM simulations. This provides valuable references for the enterprises' decision making and the governments' policymaking to facilitate the diffusion of prefabricated building technologies.

Fuzzy Cognitive Map

FCM is a soft computing approach that models complex systems by using experts' knowledge and perceptions (Obiedat & Samarasinghe, 2016). It produces a signed directed graph consisting of nodes standing for the concepts within a system and connections representing the causal relationships among concepts (Misthos et al., 2017). The graphical representation of FCM demonstrates the concepts that can exert influence on other concepts, showing the interconnections between concepts and how much the influence is. Based on the signed directed graph, FCM can model the effect of different interventions on the systems by altering the initial values of the concepts and subsequently conducting computer simulations (Meliadou et al., 2012; Reckien, 2014).

The application of FCM in previous studies

FCM is able to specify the relationships between related concepts of a system and identify its structural properties and dynamics (Azadeh et al., 2014). Meanwhile, FCM can extract knowledge from diverse sources, such as different stakeholder groups, and thus it could reveal the areas of consensus and diverging views from stakeholder groups (Bosma et al., 2017). Because of its above merits, FCM has been used in various areas of studies, such as politics (Christen et al., 2015; Kontogianni et al., 2012), social-ecological systems (Obiedat et al., 2016; Vanwindekens et al., 2013), socio-economical systems (Kontogianni et al., 2013), the agriculture sector (Rajaram et al., 2010; Vanwindekens et al., 2013), urban management (Olazabal & Pascual, 2016), environment management (Azadeh et al., 2014; Zhang et al., 2013), and the energy sector (Huang et al., 2013). However, the applications of FCM in the area of construction innovation are very limited. As Li et al. (2014) highlighted, the diffusion of prefabricated building technology is highly complex. With the aid of FCM, the complex interactions among the factors impacting prefabricated building technologies can be identified which is valuable for effective policy-making promoting prefabrication (Huang et al., 2013).

Procedures of FCMs

FCM construction and aggregation

Nodes in the FCM represent the concepts in the system. They are connected by signed and weighted arcs which stand for causal relationships amongst the concepts (Shen et al., 2017). Concepts are interconnected with arcs (e_{ij}) with different weights (w_{ij}). The interconnection e_{ij} between two concepts C_i and C_j indicates causal flows from C_i to C_j, and the weights can express positive, negative or neutral causality and take values in the space [-1, 1] (Kyriakarakos et al., 2014).

Condensation is used to aggregate the variables of individual FCM into higher–level FCM (Misthos et al., 2017; Reckien, 2014). As the quantitative condensation approach has limitations such as information loss, the qualitative condensation approach has been strongly recommended (Obiedat et al., 2016). In qualitative condensation approach, similar or related variables were grouped into high-level categories, with the connection weights summed into an overall linguistic value first and then defuzzied into numerical values in the interval [-1, 1] (Özesmi & Özesmi, 2004; Zhang et al., 2013).

FCM indices

An FCM analysis is conducted by using the Graph Theory and Social Network Analysis (Misthos et al., 2017). Generally, graph indices, including the density and complexity indices, are used to analyze the content and structure of FCMs, and the centrality index is used to measure the relative importance of each concept within individual FCM (Bosma et al., 2017; Misthos et al., 2017; Özesmi et al., 2004).

The density of a FCM is an index of connectivity, representing how connected or sparse the maps are (Zhang et al., 2013). To measure the density [D], the number of connections is divided by the maximum number of connections possible between concepts (Özesmi et al., 2004).

$$D = \frac{C}{N^2}$$

where, N is the number of variables and C is the number of connections.

As for the variables (nodes), there are three categories of nodes based on their out-degree and in-degree, namely receivers, transmitters and the ordinary nodes. Receivers have a positive in-degree and zero out-degree, while transmitters have a positive out-degree and zero in-degree. By contrast, the ordinary variables have a non-zero in-degree and out-degree (Zhang et al., 2013). The share of the number of receiver variables (R) with respect to the total number of transmitter variables (T) is used to denote the index of the complexity [Com] of a map (Bosma et al., 2017; Zhang et al., 2013).

$$Com = \frac{R}{T}$$

The centrality [Cen] is an index used to measure the level of connectedness of a variable with other variables (Bosma et al., 2017). It is measured by the summation of variables' out-degree and in-degree (Misthos et al., 2017). The calculation equation of out-degree $od(C_i)$ and in-degree $id(C_i)$ is as follows:

$$od(C_i) = \sum_{j=1}^{N} \overline{w_{ij}}$$

where N is the number of nodes connected from node C_i in the FCM, and (w_{ij}) is the weight of the connection from node C_i to node C_j.

$$id(c_i) = \sum_{j=1}^{N} \overline{w_{ij}}$$

where N is the number of nodes connected to node C_i in the FCM, and (w_{ij}) is the weight of the connection entering node C_i from node C_j.

$$\mathrm{Cen}_D(c_i) = od(C_i) + id(C_i)$$

FCM Simulation

The system simulation can help to explore how the studied system evolves in different scenarios (Bosma et al., 2017). The mathematical model of FCM consists of a [$1 \times n$] state vector which includes the values of the concepts and a [$n \times n$] weight matrix W, gathering the weight w_{ij} of the interconnections amongst concepts in the FCM (Büyüközkan & Vardaloğlu, 2012). The dynamics of the FCM model are illustrated by these matrices and updated through iteration with other concepts (Shen et al., 2017). At each simulation step, the value A_i of a concept C_i is calculated by computing the effect of the interconnected variable c_j on the specific variable c_i (Kosko, 1986). After a set of iterations, the values of concepts will evolve until being stabilized at a fixed point, and then, a final vector A is obtained.

$$A_i^{(k+1)} = f(A^k + \sum_{\substack{j \neq i \\ j=1}}^{N} A^k * W_{ji})$$

where $A_\mathrm{i}^{(k+1)}$ is the value of concept C_i at step $k+1$, $A_j^{(k)}$ is the value of concept C_j at step k, f is the threshold function, W_{ij} is the weight of the interconnection between C_i and C_j.

Research procedure

Data collection

Primary data for this study were collected through semi-structured interviews with critical stakeholders relevant to prefabricated building technologies in Chongqing, China. As a large and densely populated urban center located in Southwestern China, Chongqing has a large construction sector (Gan et al., 2018a). In 2016, the GDP growth rate of Chongqing was 10.7%, 4% higher than the national average. The urbanization rate is expected to rise from 60.9% in 2015 to above 75% in 2030 according to the *Population Development Plan of Chongqing City (2016-2030)* issued by the Chongqing Municipal Government in 2017. This suggests there will be a high volume of building practices in Chongqing in the future. The steel and automobile industries are the economic pillars for Chongqing, demonstrating that Chongqing possesses strong manufacturing capability needed for the promotion of prefabricated building technologies (Arif & Egbu, 2010; Pan et al., 2011). In 2016, the Chongqing Municipal Government issued *Guidance on Accelerating* *the Industrial Innovations for Applications of Steel Structure* to promote steel-structure prefabricated buildings. However, the construction industry in Chongqing is still dominated by the traditional onsite construction methods, partially resulting in the issues of poor quality, excessive time and the mismatch between design and construction (Pan et al., 2011). The total floor space under construction in Chongqing was 219.7 million m^2 in 2015 (CQSB, 2015). According to the Chongqing Urban-rural Construction Committee, the buildings adopting prefabricated building technologies only account for less than 5% of new building construction in 2016.

Six categories of stakeholders including government, developers, designers, contractors, manufacturers and researchers in Chongqing were chosen because of their critical role in prefabrication (Li et al., 2014; Teng et al., 2017; Xue et al., 2017). Despite great influence exerted on prefabricated buildings (Li et al., 2014), house buyers were not chosen due to their limited knowledge and expertise. Each interview was conducted with one interviewee, providing participants with more freedom and flexibility so that they can discuss the problem from their own knowledge and perceptions (Obiedat et al., 2016). In total, 39 individuals agreed to participate in the interviews. The profiles of interviewees were presented in Table 1. 53.8% of the interviewees had more than 5 years of experience in the field of prefabricated building technologies, including 17.9% of interviewees with more than 10 years of experience. 12.9% of the interviewees are from government agencies, and other interviewees represent developers (15.4%), contractors (20.5%), designers (17.9%), manufacturers (15.4%) and researchers (17.9%).

<Insert Table 1 here>

The semi-structured interviews took place during September and October 2017. Each interview lasted for at least 35 minutes. Before each interview, the methodology of FCM was explained to the interviewees. Once the participants understood the process of FCM, they were asked to list impeding factors to the adoption of prefabricated building technologies. They were given sufficient time to contemplate any factors they considered important (Bosma et al., 2017). Then, they were required to describe the type of interconnected relationships among these factors and assess the strength of these relationships. Arrows were used to indicate how these factors interrelate and the fuzzy set of the linguistic variables were adopted to describe the strength of the impact that one factor has on the other. With reference to similar research, e.g., Kyriakarakos et al. (2014) and Büyüközkan et al. (2012), the adopted linguistic variables comprise: negatively very strong, negatively strong, negatively medium, negatively weak, zero, positively weak, positively medium, positively strong and positively very strong.

Data analysis

The data analysis proceeds based on the framework shown in Fig.1. There are five main steps in the data processing process, as marked in Fig. 1. Firstly, by using in-depth qualitative interviews, factors impacting the diffusion of prefabrication technologies were identified, along with the weights of the relationships amongst factors. The identified factors and weights obtained from each interviewee were used to construct the individual FCM. Then, the various individual FCMs were aggregated into stakeholder-grouped FCM through the approach of qualitative condensation.

<Insert Fig. 1. here>

Fig.1. Research procedure and methodologies

Regarding the stakeholder-grouped FCMs, two analyses were conducted, namely the comparative analysis of graph indices (the density and complexity indices), as well as the identification of the most frequently mentioned factors by each stakeholder group, which help to identify the most important impediments to the diffusion of prefabricated building technologies (Zhang et al., 2013). In this study, the most frequently mentioned factors were those mentioned by at least two-thirds of interviewees in a stakeholder group. The stakeholder-grouped FCMs were then aggregated into a collective FCM through condensation. Three types of analyses were subsequently employed to examine the collective FCM, namely the graph indices analysis, centrality indices analysis and the FCM simulations. The centrality indices analysis helps to identify the most central factors in the collective FCM. These factors are the basis of the following FCM simulations, which produce a series of "what-if" scenarios to test the effects of various interventions to promote prefabrication. The various interventions were reflected by the proportional changes made to the identified most central variables in the collective FCM. After the simulation, comparisons between the new state and the previous state of the FCM variables reveals the influence of the intervention on the system outcomes. The intervention that could lead to the largest absolute value of the difference between the new state and previous state of the FCM variables is the most effective intervention to promote the diffusion of prefabrication technologies.

Results

Stakeholder-grouped FCMs

The contents mentioned by interviewees were classified and grouped into 13 factors from three perspectives namely the technological, organizational and environmental perspectives, as shown in Table 2 (Xue et al., 2017). Factors related to technology include cost, logistics, quality and aesthetics, and the organizational factors impacting prefabrication include manufacturing capability, project process, project management, knowledge and expertise, and business model. Apart from these factors which could be influenced by the enterprises related to prefabrication, some external factors could also impact the diffusion of prefabrication technologies such as market demand, social climate, codes and standards, as well as policies and regulations.

<Insert Table 2 here>

After the completion of each interview, one FCM was created for each interviewee, resulting in a total of 39 FCMs providing a direct understanding of each participant's knowledge and perceptions. The number of citations of each factor in these FCMs revealed the top 7 most frequently mentioned factors in each stakeholder group, as shown in Table 3. In general, the most frequently mentioned factors were mainly related to the technological and environmental aspects. Three factors, namely cost, market demand, and policies and regulations, were most frequently mentioned by all stakeholder groups. This suggests there is a common perception that the prefabricated building technologies are strongly affected by these factors. For S1 (the government), S2 (developers), S4 (contractors) and S5 (researchers), the factors were relatively evenly distributed in the three aspects, while for S3 (designers) and S6 (manufacturers), the factors in the technology and environment aspects were more frequently mentioned than other aspects. Some factors were ranked in the top 7 most frequently mentioned factors only in one stakeholder group, e.g., aesthetic performance by S3 (designers), and business model by S2 (developers).

<Insert Table 3 here>

The stakeholder-grouped FCMs are composed of the factors and their relationships. According to Azadeh et al. (2014), only the interactions between factors with the value more than 0.05 or less than -0.05 need to be retained in the FCM. The graph indices obtained from the stakeholder-grouped FCMs are presented in Table 4. It is interesting to note that there is a similar structural property existing in all the stakeholder groups. Specifically, the number of transmitter concepts in all stakeholder groups was 1, and the number of receiver concepts in all stakeholder groups was 0. Similarly, the number of ordinary concepts in all stakeholder groups was 12. The high number of ordinary factors indicates that most factors have mutual relationships with each other, namely being influenced by and influencing other factors simultaneously (Christen et al., 2015).

<Insert Table 4 here>

Collective FCM

The stakeholder-grouped FCMs were further combined into the collective FCM. The UCINET software visualizes the collective FCM as shown in Fig 2. The last column of Table 4 shows the graph indices of the collective FCM. There is only one transmitter factor and the rest are all ordinary factors. This is consistent with all the stakeholder-grouped FCMs. The density equals to 0.308, which indicates the connectivity among factors was moderate.

<Insert Fig. 2. here>

Fig.2. The visualization of collective FCM

As shown in Table 5, all factors in the technology aspect have a higher value of in-degree than that of out-degree, which indicates that these factors are more likely to be influenced by other factors rather than influencing other factors. Thus, the technological factors have a receiver character. On the contrary, all factors in the organizational aspect have an equal or higher value of out-degree than that of in-degree, suggesting they are more of a transmitter character. As for the factors in the environmental aspect, some of them are more influenced by other factors while the others such as F13 (policies and regulations) influence other factors more. A closer examination of the collective FCM reveals that the connections starting from organizational factors largely end on technological factors, and the connections end on organizational factors are mainly from factors in the environmental aspect. This indicates that the organizational factors can exert influence on the technological factors and are also affected by factors in the environmental aspect.

<Insert Table 5 here>

As shown in Table 5, three factors have high centrality indices, namely F8 (knowledge and expertise), F1 (cost) and F13 (policies and regulations). Meanwhile, with the centrality indices higher than the mean (0.59), three factors can also be regarded as central factors, namely F10 (market demand), F6 (project process) and F3 (quality). Thus, there are a total of six important factors, playing a central role in the collective FCM. These six central factors were chosen to run the 'what-if' simulations. The initial steady state was obtained by multiplying the adjacency matrix with the initial steady state vector. For the simulations, these six factors were set to 0 one by one to represent that the corresponding barrier was eliminated, which is an intervention, resulting in six simulations. By using the software of MATLAB, the steady state of each "what-if'" scenario was obtained, as shown in Table 6. By summing up the DF of all the factors in each "what-if'" scenario, the accumulative effect of each intervention on other 12 factors was obtained, as shown in the last row of Table 6. It can be concluded that changing policies and regulations has the largest accumulated effect on other factors. Similarly, strengthening knowledge and expertise, and market demand also has strong effects on other factors. By contrast, at this stage it seems emphasizing cost, quality and project process has a relatively low

<Insert Table 6 here>

Specifically, in the "what-if" scenario of F13 (policies and regulations), the simulation shows tackling the policy barriers could lead to relatively strong changes in F12 (codes and standards), F8 (knowledge and expertise) and F9 (business model), as well as moderate changes in F2 (logistics), F5 (manufacture capability), and F6 (project process). Following stressing policies and regulations, enhancing market demand generate the second strongest cumulative effects on promoting prefabricated building technology. The simulation shows that after this intervention, the higher decreasing barriers are F9 (business model), F8 (knowledge and expertise), and F5 (manufacture capability), followed by F1 (cost). Similarly, in the simulation of F8 (knowledge and expertise), tackling knowledge barriers could lead to relatively strong changes in F12 (codes and standards), F2 (logistics), and F4 (aesthetic performance), and relatively moderate changes in F3 (quality), F7 (project management), and F11 (social climate). It seems that working on policies and regulations could alleviate the organizational and environmental barriers more than the technological barriers, while enhancing market demand generate strong effects on technological and organizational barriers. By contrast, improving the knowledge and expertise alleviate the technological barriers more. The other three "what-if" scenario simulations show a relatively weak effect. Specifically, regarding the simulation of project process, large effects are shown on the barriers of F2 (logistic), F4 (aesthetic performance), and F7 (project management). Similarly, improving quality and reducing cost both could decrease the bottlenecks regarding to F10 (market demand) and F11 (social climate). This revealed that addressing the issue of "cost" and "quality" can alleviate the barriers in the environmental aspect.

Discussions and implications

The results shown in Table 3 indicate three factors, namely cost, marker demand, policies and regulations, were perceived by all stakeholders as important barriers to the diffusion of prefabricated building technologies. The importance of market demand was overlooked by previous studies, e.g., Zhang et al. (2014), Polat (2010), Jaillon and Poon (2008), Pan et al. (2007) and Zhai et al. (2014). As Mao et al. (2015) highlighted, it is the market demand that directly influences the popularity of construction technology. Lack of market demand prohibits stakeholders to adopt innovative approaches to construction (Chang et al., 2017a). Furthermore, it is important to note that some barriers were particularly critical for certain stakeholders. For instance, aesthetic performance was only mentioned by S3 (designers) frequently, and business model was only mentioned by S2 (developers) frequently. Market demand was the most frequently mentioned factor by S1 (government) and S6 (manufacturer), but it is at the bottom of the most frequently mentioned factor lists of S3 (designer) and S4 (contractor). Stakeholders tend to concern more about the inhibitors impeding their own activities with less attention to other factors (Zhao et al., 2016a). Due to their different role and functions, stakeholders could encounter different impediments leading to diverged perceptions on the prefabricated building technology. This leads to a challenge, namely making effective measurements to motivate all the stakeholders to adopt prefabricated building technology. As suggested by Zhang et al. (2013), a participatory system should be developed to facilitate the communication among the related stakeholders, so that a shared vision and understanding of prefabricated building technology could be formed.

A large number of ordinary factors was found in the six stakeholder-grouped FCMs as well as the collective FCM shown in Table 4. This suggests that these barriers interact with each other, which reaffirmed the necessity of exploring the interactions among barriers. The visualization of the collective FCM yields a detailed picture of how these barriers interact. It is interesting to note that the barriers in the technological aspect are mainly affected by the organizational barriers, which were influenced by environmental barriers. And the environmental barriers were largely affected by barriers in the technological aspect. This indicates that the interactions among these ordinary factors present a vicious cycle. For instance, barriers in the technological aspect, e.g., high cost and low quality, were perceived to be affected by organizational barriers such as low manufacturing capability, which was affected by environmental barriers e.g. low market demand, which in turn was influenced by the high cost and low quality. Thus, the interactions amongst barriers lead to a vicious cycle inhibiting the diffusion of prefabricated building technology.

As suggested by Christen et al. (2015), the anchoring points to weakening the vicious cycles should be the factors that are not part of the cycle, namely the transmitter. Only one transmitter was found in the collective FCM: policies and regulations. This highlights the leading role of the government in promoting the adoption of prefabricated building technologies. In other industries, the clients may take the leading role in innovation, as the competitive market drives enterprises to find new solutions to remain competitive (Winch, 1998). For instance, it is the clients that take the leading role in the markets of motor cars, electrical goods, etc., where if the enterprises do not innovate, they would fail or be taken over by others who innovate (Courtney, 2009). The unique features of buildings, such as the localization of its market create lock-in mechanisms favoring the traditional approach of construction (Courtney, 2009; Reichstein et al., 2005; Xue et al., 2017). As a result, the adoption of prefabricated building technologies might be considered of adding risks to the well-established practice. Therefore, the promotion of prefabricated building technologies solely based on market-driven mechanisms might be limited. Indeed, as Mao et al. (2015) argued, the few related policies and schemes proposed for prefabricated buildings issued in China have mostly failed in their execution due to the voluntary nature of the schemes. Therefore, it is suggested that mandatory regulations and policies could be studied and issued by the government.

Six important factors that play a central role in the collective FCM were identified based on their centrality indices as shown in Table 5. By conducting the "what-if" scenario simulations of these six central factors, the effects of these interventions were shown in Table 6. Two most critical factors were identified by the simulations, namely policies and regulations, as well as knowledge and expertise. Even though improving knowledge and expertise generates a weaker cumulative effect than enhancing the market demand, it shows a more holistic effect on more barriers to prefabricated building technologies. For instance, the "what-if" scenario of simulating knowledge and expertise reveals that improving knowledge and expertise can significantly improve the logistic and aesthetic performance of prefabricated buildings. By improving policies and the knowledge base, the barriers in all the three dimensions, namely technology, organization and social environment, can be alleviated to some degree. For instance, by improving knowledge and expertise in the industry, the barriers of F2, F3, F4, F5, F7, F11, F12 can all be mitigated.

Therefore, measures should be undertaken to study and issue effective policies, as well as enhance the knowledge base and expertise for prefabricated building technologies. It is recommended that the government should allocate monetary and human resources to investigate the current status of prefabricated building development in China and formulate specific policies to facilitate industry development. For instance, the demonstration projects of prefabricated buildings could be developed, which could become a platform for information exchange and learning for prefabricated buildings and attract a broader scope of public and enterprises to get interested in prefabricated building technologies. Research and development funding could be provided to relevant academic institutions and enterprises to jointly conduct academic research on prefabricated building technologies, as well as to explore the way to commercialize these technologies in the market.

However, strengthening the policies and knowledge base is not enough for promoting prefabricated buildings, as this study reveals that some barriers cannot be adequately addressed by these measures, such as the barriers relevant to F1 (cost) and F10 (market demand), as shown in Table 6. The simulations identify that enhancing market demand is more effective than policies and regulations to reduce the cost of prefabricated building technologies and improving the quality of prefabricated buildings, which could, in turn, increase the market demand. Therefore, the vicious cycle could be turned into a virtuous circle if strategies could be developed to either enhance the market demand or improve the quality and reduce the cost of prefabrication, as they are mutually reinforced. It could be studied whether incentives and subsidies can be given to developers to use prefabrication technologies, or the clients and customers who purchase these projects, so that the market demand for prefabrication technologies can be stimulated. As market demand and cost/quality are mutually reinforced, once the market demand is increased, it is expected that the cost could be reduced, and quality could be improved due to the market competition mechanisms.

To summarize, this study provides the following practical suggestions to promote prefabricated building technologies.

- Establish an information exchange platform for prefabrication to enable the communications between different stakeholders. This study reveals stakeholders tend to concern more about the inhibitors impeding their own activities with less attention to other factors. An information exchange platform could help to eliminate information asymmetry and facilitate the formation of a shared vision for prefabrication. Such a platform could also facilitate the dissemination of cutting-edge knowledge on prefabrication, such as integrating building information modeling into prefabrication (Lu et al., 2017).
- Mandatory policies and regulations on prefabrication could be studied and issued by the government. This study reveals the factor of policies and regulations is the only transmitter in the collective FCM, impacting the vicious cycle formed by other factors. Previous studies such as Mao et al. (2015) have indicated the deficiency of the voluntary government schemes for prefabrication in China. Therefore, mandatory schemes for prefabrication should be now considered. China has successfully used different kinds of mandatory schemes to significantly promote the renewable energy industry (Zhao & Chang, 2013; Zhao et al., 2016b). Relevant lessons could be drawn on to promote prefabrication.
- Knowledge and expertise on prefabrication need to be strengthened through various means. This study reveals improving knowledge and expertise generates a holistic effect on various barriers to prefabrication. As the knowledge of prefabricated building technologies currently has not been given priority by the Chinese higher education institutions, it is imperative to develop new subjects and update the academic curricula to include prefabrication knowledge in civil engineering and architecture programs. Professional training programs should also be made available for practitioners.
- Stimulate market demand is the key to reduce production cost and improve the quality of prefabrication.

Through FCM simulations, this study reveals enhancing market demand is critical to reducing the cost and improving the quality of prefabricated building technologies. The government could consider providing financial supports or economic incentives such as low-interest loans and tax reduction for developers and customers to offset the additional cost incurred by the development or purchase of prefabricated buildings. This could stimulate market demand, which leads to increasing competition among the companies. Driven by market competition and economies of scale, companies will then improve the quality and reduce the production cost of prefabrication.

Conclusions

This study explored the interactions of factors impeding the adoption of prefabricated building technologies by taking China as an example. The perceptions on prefabricated building technologies from six critical stakeholders, namely the government, developers, designers, contractors, manufacturers and researchers, are investigated in this study using FCMs, which produce six stakeholder-grouped FCMs and the collective FCM.

Firstly, 13 factors impeding the diffusion of prefabrication were identified using in-depth interviews with 39 participants from six critical stakeholders. Then, by aggregating the weights of the relationships among these factors, six stakeholder-grouped FCMs, as well as the collective FCM, were generated. The density index, complexity index, and centrality index of FCMs were examined. Finally, by conducting the "what-if" scenario simulations of six critical factors, this study simulated the effectiveness of different intervention strategies on alleviating barriers to prefabrication. The research results imply that it is necessary to understand all relevant stakeholders' perceptions. Three factors including market demand, cost and policies and regulations have been mentioned by all stakeholder groups in this study. However, these factors were ranked differently by stakeholder groups, implying that they perceive the barriers to prefabricated building technologies differently. The collective FCM shows the complex relationships among these barriers, and therefore without conducting simulations, it is difficult to evaluate tackling which barrier could generate the strongest promotion effect on prefabricated buildings. The simulation results show that improving policies and regulations could generate the strongest cumulative effect on alleviating other barriers, followed by strengthening market demand and knowledge and expertise. It is suggested that the leading role should be played by the government through effective policies and regulations, while other measures addressing factors such as knowledge and expertise are also necessary.

Theoretically, this study explored the complexity involved in the diffusion of prefabricated building technologies. This study complements previous studies solely identifying and ranking the factors impeding prefabrication, by analyzing the interactions among these factors through FCM simulations, which has not been employed in previous studies on prefabrication. Practically, this study provided four policy recommendations based on rigorous FCM simulations, namely establishing an information exchange platform, considering mandatory policies and regulations, strengthening knowledge and expertise through various means, and stimulating market demand to reduce cost and improve quality of prefabrication.

This study provides an in-depth understanding of the interactions among barriers to the diffusion of prefabricated building technologies by using FCM approach. One limitation is that the data of this study is from China where prefabricated buildings are in the initial development stage and thus may face stronger barriers compared to the countries where prefabricated building technologies have become more accepted. Future studies could be conducted to investigate regions in other countries so that international comparisons for promoting prefabricated building technologies could be explored.

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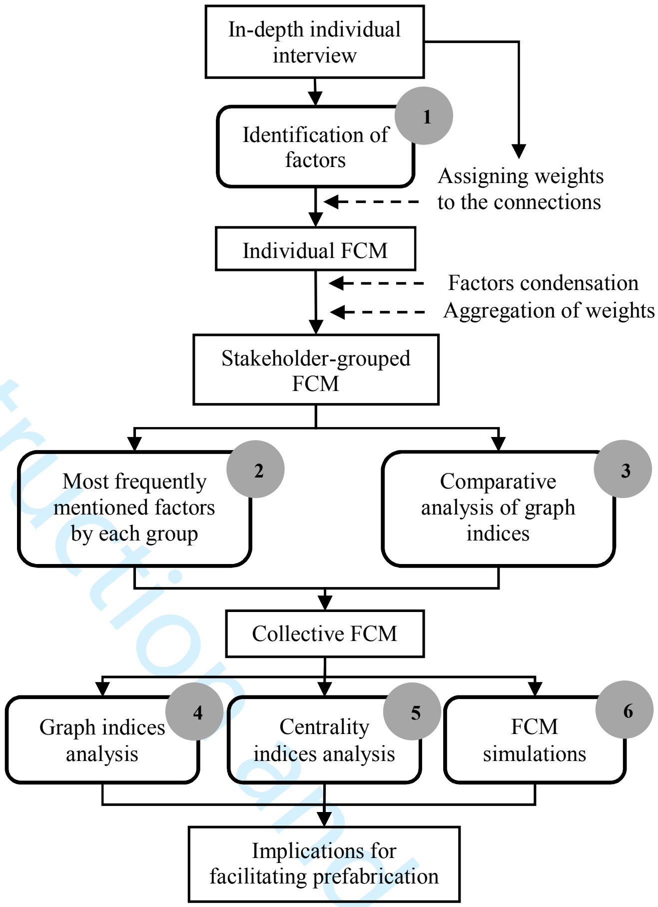
In-depth individual interview
Identification of factors
1
Assigning weights to the connections
Individual FCM
Factors condensation
Aggregation of weights
Stakeholder-grouped FCM
Most frequently mentioned factors by each group
2
Comparative analysis of graph indices
3
Collective FCM
Graph indices analysis
4
Centrality indices analysis
5
FCM simulations
6
Implications for facilitating prefabrication

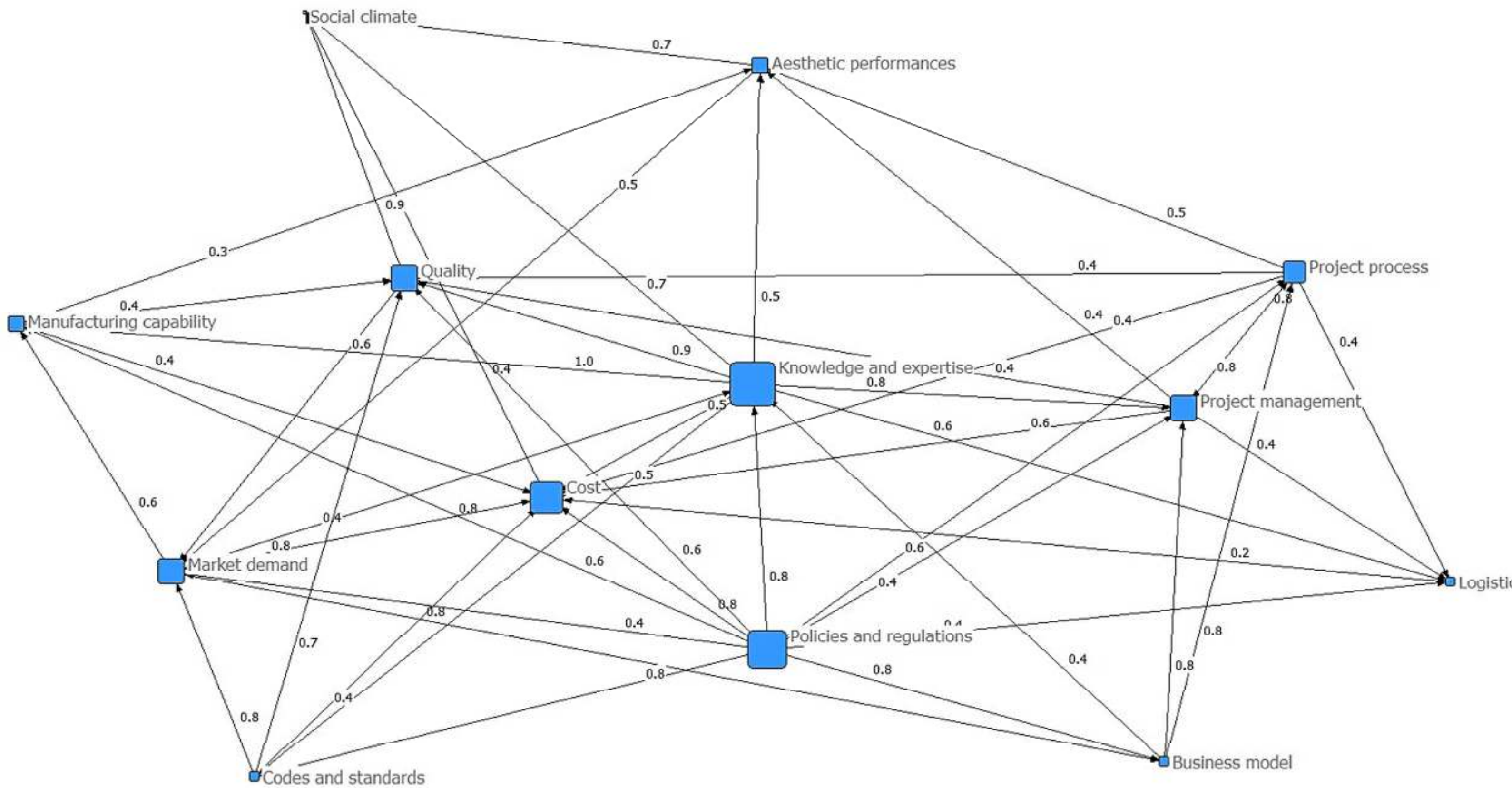
Social climate
Aesthetic performances
Quality
Project process
Manufacturing capability
Knowledge and expertise
Project management
Cost
Market demand
Logistic
Policies and regulations
Codes and standards
Business model

Table 1. Profiles of interviewees

	Profile	Number	Percentages
Organization type	Government	5	12.9%
	Developer	6	15.4%
	Contractor	8	20.5%
	Designer	7	17.9%
	Manufacturer	6	15.4%
	Research institution	7	17.9%
Job position	Professor and associate professor	7	17.9%
	Project manager	6	15.4%
	Engineer	7	17.9%
	Senior manager	8	20.5%
	Chief manager	5	12.9%
	Director	6	15.4%
Working years	<2	0	0
	2~5	18	46.2%
	5~10	14	35.9%
	>10	7	17.9%

Table 2. Factors impeding the adoption of prefabricated building technologies identified by stakeholders

Dimensions	Code	Factors	Relevant contents mentioned by interviewees
Technology	F1	Cost	• High initial cost, high construction cost, high-cost pressure, high design fee, high transportation cost, long payback period, high labor cost, cost uncertainty, etc.
	F2	Logistics	• Long distance of transportation, damage during transportation, transportation limitation, increased accidents on site, limited space for storing, etc.
	F3	Quality	• Unproven durability, defective connections and deformation, leakage problems, wall cracks, poor sound insulation, high moisture, incompatibility problems, etc.
	F4	Aesthetic performance	• Monotonous design, poor creativity, the monotony of structure type, poor design diversity, repetition of layouts, etc.
Organization	F5	Manufacturing capability	• Lack of customization, the incompetence of small-size companies, the monopoly of techniques by few firms, lack of mature and tested supply chains, limited supply bases, etc.
	F6	Project process	• Complicated interfaces, unable to confirm design early, conflict with traditional project process, late deliveries.
	F7	Project management	• Lack of management experiences, unfavorable organizational culture, poor cooperation, lack of information sharing, etc.
	F8	Knowledge and expertise	• Little experience of contractors, the low competence of suppliers, lack of qualified labor workers, the limited expertise in inspection, lack of training and education, etc.
	F9	Business model	• Dominate importance of land acquisition, contractual risks, excessive competition, fragmented industry structure, unfavorable industry funding model, etc.
Environment	F10	Market demand	• The uncertainty of market demand, limited market demand, protection from traditional suppliers, etc.
	F11	Social climate	• Stigma from the previous failures, lack awareness of benefits, risk-averse culture, purchasers' conservation and skepticism, lacking financial support, etc.
	F12	Codes and standards	• Low standardization, lacking peremptory industry norms, lack of a nationwide standards, improper design code, limited R & D activities in codes, etc.
	F13	Policies and regulations	• Unavailability of the legal frameworks, lack of financial incentives, limited supporting policies, lack of mandatory regulations, inadequate policies instruments, etc.

Table 3. Most frequently mentioned factors by stakeholder groups

Aspect	Factor	S1	S2	S3	S4	S5	S6
Technology	Cost	4	1	3	2	4	5
	Logistics						6
	Quality	6	4		5	5	7
	Aesthetic performance			2			
Organization	Manufacturing capability	5				6	2
	Project process				4		
	Project management		7		7		
	Knowledge and expertise	2		7	1	2	
	Business model		5				
Environment	Market demand	1	2	6	6	3	1
	Social climate		6	5			
	Codes and standards	7		1		7	3
	Policies and regulations	3	3	4	3	1	4

Notes: The number in cell refers to the ranking of factors by citations through each stakeholder group. S1 refers to the Government, S2 refers to Developers, S3 refers to Designers, S4 refers to Contractors, S5 refers to Researchers, S6 refers to Manufacturers.

Table 4. Graph indices of stakeholder-grouped FCMs and collective FCM.

Graph indices	S1	S2	S3	S4	S5	S6	All
Number of connections	74	68	44	49	37	43	48
Number of transmitter concepts	1	1	1	1	1	1	1
Number of receiver concepts	0	0	0	0	0	0	0
Number of ordinary concepts	12	12	12	12	12	12	12
Density	0.474	0.436	0.282	0.314	0.237	0.286	0.308
Complexity	0	0	0	0	0	0	0

Notes: **S1** refers to the Government, **S2** refers to Developers, **S3** refers to Designers, **S4** refers to Contractors, **S5** refers to Researchers, **S6** refers to Manufacturers, and All refers to collective FCM.

Table 5. The centrality indices for the collective FCM

No	Dimensions	Condensed Factors	In-degree centrality	Out-degree centrality	Centrality	Character
F1	Technology	Cost	0.667	0.167	0.833	R
F2		Logistics	0.333	0.083	0.417	R
F3		Quality	0.500	0.167	0.667	R
F4		Aesthetic performance	0.333	0.167	0.500	R
F5		Manufacturing capability	0.250	0.250	0.500	T=R
F6	Organization	Project process	0.250	0.417	0.667	T
F7		Project management	0.167	0.333	0.500	T
F8		Knowledge and expertise	0.250	0.667	0.917	T
F9		Business model	0.167	0.250	0.417	T
F10	Environment	Market demand	0.417	0.333	0.750	R
F11		Social climate	0.333	0.083	0.417	R
F12		Codes and standards	0.167	0.167	0.333	T=R
F13		Policies and regulations	0.000	0.833	0.833	T

Notes: T refers to the factors have more of a transmitter character (out-degree＞in-degree), R refers to the factors have more of a receiver character (out-degree < in-degree).

Table 6. The results of FCM simulations

	ISS	Cost (F1)		Quality (F3)		Project process (F6)		Knowledge and expertise (F8)		Market demand (F10)		Policies and regulations (F13)	
		SSS	DF	SSS	DF	SSS	DF	SSS	DF	SSS	DF	SSS	DF
F1	0.991	**0.000**	-0.991	0.991	0.000	0.986	-0.005	0.983	-0.007	0.979	-0.012	0.983	-0.008
F2	0.925	0.925	0.000	0.925	0.000	0.884	-0.040	0.874	-0.050	0.922	-0.003	0.893	-0.031
F3	0.981	0.981	0.000	**0.000**	-0.981	0.971	-0.010	0.955	-0.027	0.980	-0.002	0.968	-0.014
F4	0.921	0.921	0.000	0.921	0.000	0.875	-0.046	0.875	-0.046	0.917	-0.004	0.916	-0.005
F5	0.946	0.945	-0.001	0.945	-0.001	0.945	0.000	0.970	0.025	0.894	-0.052	0.912	-0.034
F6	0.948	0.948	0.000	0.948	0.000	**0.000**	-0.948	0.947	-0.001	0.943	-0.005	0.916	-0.032
F7	0.970	0.970	0.000	0.970	0.000	0.935	-0.035	0.939	-0.031	0.965	-0.005	0.954	-0.016
F8	0.902	0.901	-0.001	0.901	-0.001	0.902	0.000	**0.000**	-0.902	0.843	-0.059	0.833	-0.069
F9	0.908	0.906	-0.002	0.906	-0.001	0.908	0.000	0.908	0.000	0.794	-0.114	0.840	-0.068
F10	0.980	0.954	-0.025	0.963	-0.017	0.979	-0.001	0.978	-0.001	**0.000**	-0.980	0.973	-0.007
F11	0.972	0.958	-0.014	0.934	-0.038	0.971	-0.001	0.944	-0.029	0.971	-0.001	0.970	-0.002
F12	0.870	0.870	0.000	0.870	0.000	0.870	0.000	0.794	-0.076	0.866	-0.004	0.771	-0.099
F13	0.659	0.659	0.000	0.659	0.000	0.659	0.000	0.659	0.000	0.659	0.000	**0.000**	-0.659
SUM			-0.043		-0.058		-0.138		-0.243		-0.261		-0.385

NOTES: ISS=Initial Steady State; SSS=Simulation Steady State; DF=Difference between SSS and ISS; SUM=the cumulative changes of the other 12 factors caused by the altered factor.