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Fuzzy modelling of the critical failure factors for modular integrated construction projects

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Abstract

Modular integrated construction (MiC) is a game-changing cleaner construction approach which improves construction project performances. For many types of buildings, MiC is increasingly becoming a preferred construction method. However, MiC projects have generated mixed outcomes; many of them encountered problems and even failed. Yet, there is limited knowledge of the reasons why MiC projects may fail. This research identified and evaluated 22 potential critical failure factors (CFFs) for MiC projects, based on a structured questionnaire survey with international experts. A mean score analysis showed that all the identified CFFs are significant factors causing MiC project failure. A structure detection analysis of the CFFs generated a 4-factor solution explaining about 72.34% of the total variance in the failure of MiC projects. The 4 principal failure factors (PFFs) for MiC projects comprises poor design and dimensional variability management, poor stakeholder and supply chain management, limited technical knowledge, capability and experience, and late commitment. A fuzzy modelling of the CFFs revealed that all the 4 PFFs are significant factors causing MiC project failure. The inclusive findings of the research have useful implications. Theoretically, the findings contribute to the useful checklist of generic CFFs for MiC projects. Practically, the research prioritized the CFFs, which may serve as a useful management-support in the implementation of MiC projects.

Keywords: critical failure factors; fuzzy modelling; modular integrated construction; projects

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1. Introduction

The intractable challenge of providing quality affordable housing, stagnating productivity, lower efficiency, increasing shortage of skilled labour, poor safety of construction workers, higher carbon emissions, large waste footprint, cost escalation, time overrun, and poor project quality control associated with the cast-in-situ construction (CSC) approach have been identified as significant threats to the competitiveness of the construction industry and risks to the realization of a sustainable modern built environment (Pan and Hon, 2018; Wuni and Shen, 2020a). These long standing problems and persistent market failures are driving transformative innovations and disruptions in the construction industry (Blismas and Wakefield, 2009; Goodier et al., 2019). One of such important disruptions and game-changing paradigms is the transition towards off-site manufacturing (OSM) of buildings (Bertram et al., 2019). OSM is cleaner and greener construction approach because it reduces carbon emissions, minimizes construction waste, reduces energy consumption, reduces construction dusts and pollution (Mao et al., 2013; Quale et al., 2012).

OSM transforms the linear fragmented site-based erection of buildings into an integrated manufacture and assembly of factory-made value-added building components (Goodier and Gibb, 2007; Pan and Hon, 2018). Modular integrated construction (MiC) constitutes one of the most complete form of OSM where over 80-95% of a building can be manufactured in an offsite factory (Smith, 2016). MiC together with associated supply chain arrangements leverages significant reduced construction time (Goodier et al., 2019), improved productivity (Building and Construction Authority, 2017), improved project quality control (Blismas et al., 2006), improved safety of construction workers (McGraw Hill Construction, 2013), reduced construction waste footprint (Tam et al., 2007b), reduced carbon emissions (Mao et al., 2013), and reduced lifecycle cost (Pan and Sidwell, 2011). MiC is increasingly becoming mainstream in the construction industry with significant investment and developed markets in regions such as Japan, Scandinavia, Germany, Australia, the United Kingdom, among others (Fraser et al., 2015).

However, several conditions and factors determine the failure or success of MiC projects (Belassi and Tukel, 1996; Sanvido et al., 1992). The success of MiC is extremely important because such outcomes may exonerate the approach from the negative stigma associated with the hastily implemented post-war prefabricated housing. However, some implemented MiC projects have shown mixed outcomes; majority of them encountered serious implementation problems and even failed to realize planned objectives and the expectations of stakeholders (Choi et al., 2016). Available evidence suggests that some countries have made significant advancement in the application of OSM techniques (Fraser et al., 2015; Hwang et al., 2018b). Considering that such economies have advanced in the MiC learning curve, the cumulative knowledge, lessons, and experiences of experts in these countries constitute an enormous asset that could be leveraged to advance general knowledge of MiC delivery and deserve to be exploited for the progress of the OSM industry. One approach to utilizing their enormous knowledge accrued over the decades of combined experiences and lessons is to solicit their informed views on the factors which determine success or failure of MiC projects.

However, existing treatises have focused on identifying and evaluating the critical success factors (Choi et al., 2016; Wuni and Shen, 2019a) and neglected the factors which predicate failure of MiC projects. As a result, there is limited knowledge of the factors and conditions which must go wrong for MiC projects to fail. This research seeks to identify and model the critical failure factors (CFFs) for MiC projects, drawing on the opinions of international experts. Considering that the assessment of CFFs is based on the subjective opinions of the experts, fuzzy logic is implemented to make objective assessment of the subjective opinions. Thus, the inclusive findings of this research will inform MiC and OSM stakeholders of the recurring factors causing MiC project failures and may form a useful management-support in MiC project delivery. The identified potential CFFs would guide MiC stakeholders in implementing appropriate strategies to overcome these failure causes and improve the success of future projects.

2. Research and theoretical background

2.1 The theory of critical failure factors

According to Belassi and Tukel (1996), a failed construction project is one that does not realize both planned objectives and the expectations of stakeholders. Sanvido et al. (1992) indicated that several factors and conditions converge to determine the failure of a construction project. The concept of CFFs emerged in the 1970s in an attempt to explain the failure of enterprise resources planning, ERP (Lyytinen, 1988; Lyytinen and Hirschheim, 1987). CFFs describe the conditions and management areas which must go wrong for an ERP project to achieve a high level of failure (Yeo, 2002). Thus, this research conceptualizes CFFs as those few conditions, factors, and management areas that must be deficient for MiC projects to achieve high level of failure. CFFs prevent MiC projects from realizing planning objectives and meeting the expectations of stakeholders. MiC project failures have various forms because of the multiplicity of planned objectives and stakeholders. Drawing on Lyytinen and Hirschheim (1987), this research classifies MiC project failures into five categories: (a) correspondence failure – occurs when the completed MiC project does not meet the design objectives and specifications; (b) process failure – occurs when the lifecycle cost of the MiC project exceeds its lifecycle benefits or when the schedule of the MiC project is significantly exceeded; (c) expectation failure – occurs when the completed MiC project does not meet the expectations, requirements or values of stakeholders; (d) sustainability failure – occurs when the project does not meet its sustainability requirements; and (e) termination failure – occurs when the MiC project is terminated before completion or abandoned during operation.

2.2 Critical failure factors for modular integrated construction projects

Given the limited published research, the CFFs for MiC projects could not be directly extracted from the literature. However, there is considerable wealth of literature on OSM project delivery which implicitly identified some failure factors. Thus, a comprehensive review and synthesis of the relevant literature was conducted to identify the potential CFFs for MiC projects. Table 1 shows a summary of the potential CFFs for MiC projects extracted from the literature review. Gibb and Neale (1997) identified that weather disruptions resulted in significant schedule overrun in the on-site installation of a complex prefabricated cladding in London.

Table 1. Potential failure factors for MiC projects

Code	Failure factors for MiC projects	References
CFF1	Inaccurate engineering specifications and late design freeze	Gibb and Isack (2003); Choi et al. (2016); Hsu et al. (2018); Wuni et al. (2019)
CFF2	Limited fabricator experience and capabilities in modules design and production	Blismas et al. (2005); Hwang et al. (2018a)
CFF3	Poor working collaboration and infrequent communication among project participants	Li et al. (2017); Hwang et al. (2018a)
CFF4	Supply chain disruptions and disturbances	Gibb and Neale (1997); Li et al. (2016); Wang et al. (2018a); Wang et al. (2018b);
CFF5	Poor coordination of fragmented supply chain segments	Li et al. (2016); Hwang et al. (2018a); Wuni et al. (2019)
CFF6	Unsuitability of design for MiC	Blismas et al. (2005);Hwang et al.(2018b)
CFF7	Non-involvement of key participants throughout the major stages of the project lifecycle	Li et al. (2016); Wuni and Shen (2019b); Hwang et al. (2018a);

CFF8	Poor client understanding, receptivity and acceptance of MiC	Blismas et al. (2005); Wuni and Shen (2019b)
CFF9	Planning and scheduling deficiencies	Choi et al. (2016); Li et al. (2018); Wuni et al. (2019)
CFF10	Use of inexperienced and incapable workforce	Blismas et al. (2005); Hwang et al. (2018b)
CFF11	Non-engagement of key participants at the earliest stage of the project	Gibb and Isack (2003); Wuni and Shen (2020b)
CFF12	Significant dimensional variabilities and site-fit-reworks	Shahtaheri et al. (2017); Enshassi et al. (2019)
CFF13	Limited skilled workforce, management and supervising team	Hwang et al. (2018a); Wuni et al. (2019)
CFF14	Late advice and consideration of MiC in the project	Murtaza et al. (1993); Blismas et al. (2005); Wuni et al. (2020)
CFF15	Unavailability of sound local transport infrastructure and site equipment capabilities	Murtaza et al. (1993); Hwang et al. (2018b); Wuni and Shen (2019b)
CFF16	Unsupportive design layout and construction	Luo et al. (2015); Hwang et al. (2018b)
CFF17	Unrealistic economic analysis and definition of MiC project scope	Blismas et al. (2005); Hwang et al. (2018b)
CFF18	Errors in modular connection on the site	Li et al. (2016); Li et al. (2018)
CFF19	Poor coordination and integration of the conflicting interests of the relevant stakeholders	Li et al. (2016); Luo et al. (2019)
CFF20	Poor skills in coordinating on-site and off-site construction interfaces	Fraser et al. (2015); Hwang et al. (2018b)
CFF21	Use of unsuitable procurement system and contracting	Tam, Tam, and Ng (2007); Fraser et al. (2015); Wuni et al. (2019)
CFF22	Ineffective stakeholder, supply chain and execution risk management	Choi et al. (2016); Luo et al. (2019)

Gibb and Isack (2003) conducted an interview survey with major construction clients in the UK and identified that late commitment; untimely design freeze; and late involvement of modules suppliers were considered CFFs for OSM projects. Blismas et al. (2005) identified late advice and commitment, limited capacity of fabricators, untimely design freeze, poor client understanding of OSM, and unrealistic economic analysis as CFFs for OSM projects. Choi et al. (2016) identified planning and scheduling deficiencies, poor risk management, untimely design freeze, and non-involvement of fabricators/suppliers as CFFs for industrial modular construction projects. Li et al. (2016) discussed how component connection errors and poor coordination of stakeholders generated significant schedule delays in prefabricated housing production in Hong Kong. Shahtaheri et al. (2017) identified significant dimensional and geometric variabilities in the building components as drivers of poor quality and site-fit-reworks in modular construction.

Hsu et al. (2018) concluded that defective design and change orders constituted CFFs in modular construction projects. Hwang et al. (2018a) conducted a questionnaire survey with practitioners in Singapore and identified that poor coordination of the fragmented supply chain segments, unsupportive design layout, inexperienced workforce and unavailability of sound transport infrastructure constituted CFFs for prefabricated prefinished volumetric construction projects. Luo et al. (2019) identified poor stakeholder coordination and poor management of stakeholder-associated risk factors as CFFs for prefabricated construction projects. Wuni et al. (2019) identified supply chain disruptions and disturbances, poor coordination and communication among project participants, ineffective stakeholder management, unsuitable design, late design freeze, on-site installation errors, and significant dimensional variabilities as the most cited CFFs for MiC projects.

3. Research design and approach

The study adopted a quantitative research design within a positivist epistemology where expert approach formed the basis for evaluating the relative significance of the CFFs for MiC projects. The research implemented a multistage methodological framework comprising a comprehensive review of literature, expert review, questionnaire design and administration, pretesting of the dataset, and modelling of the CFFs for MiC projects. Figure 1 is a flowchart of the methodological framework of the research.

3.1 Identifying the relevant CFFs for MiC projects

A two-stage approach was implemented to identify the relevant CFFs for MiC projects. First, a comprehensive review of the relevant OSM literature was conducted to identify potential CFFs for MiC projects (Table 1). Second, three MiC experts from Hong Kong, Canada and Australia were invited to review the lists of CFFs to ascertain their relevance to the failure of MiC projects. Outcomes of the expert review resulted in modifications of some of the identified CFFs. A final set of 22 CFFs formed the basis for the questionnaire design and survey.

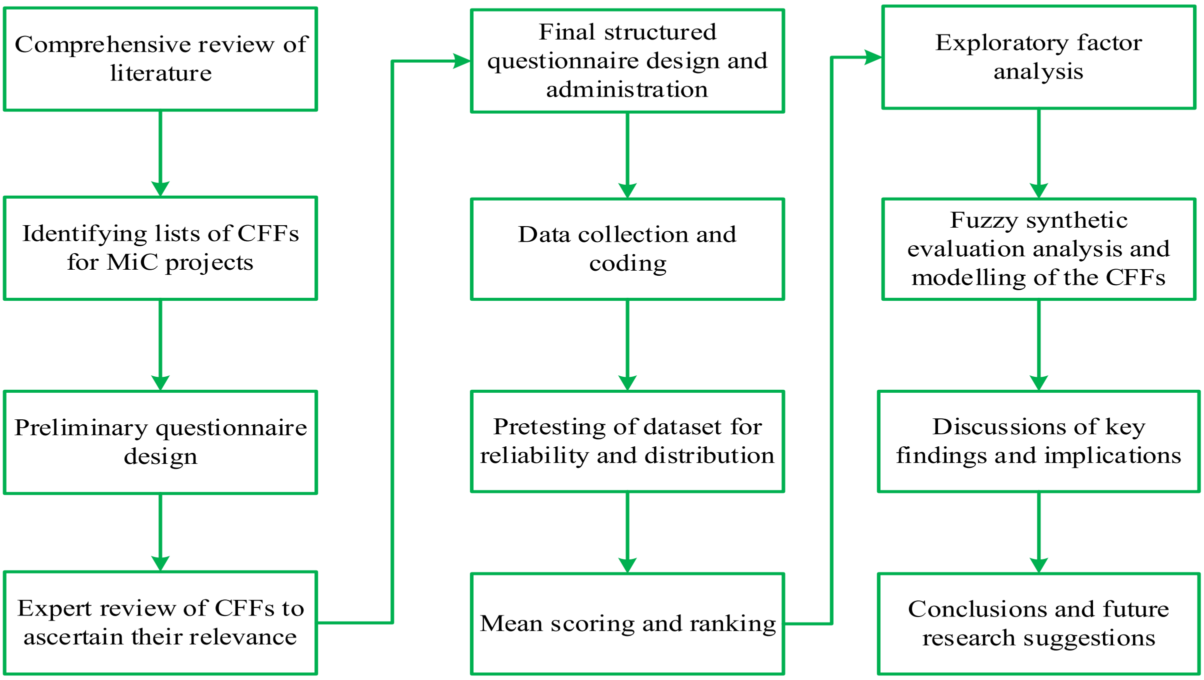

Figure 1. Methodological Framework for the Study

3.2 Questionnaire design and measurement instrument

An expert approach was adopted where the opinions of international MiC experts formed the basis for evaluating the significance of the CFFs for MiC projects. A similar approach has been used by Darko et al. (2017) and Ameyaw and Chan (2015). The expert approach influenced the use of questionnaires to solicit their opinions. Questionnaires were adopted in the study due to the following reasons: (a) the use of fuzzy logic in the study required quantitative data on the CFFs, which can be easily generated using structured questionnaires (Hwang et al., 2018b); and (b) the research draws on the cumulative experiences and knowledge of international experts which can be solicited using questionnaires. The questionnaire had two sections. Section 1 solicited relevant background information of the experts, as shown in Table 2.

Table 2. Background data of the surveyed experts

Attribute	Sub-attribute	Responses	% Responses
Years of MiC work experience	Below 10 years	40	71.4
	11 - 20 years	7	12.5
	Above 20years	9	16.1
	Total	***56***	***100.0***
Regions	North America	18	32.2
	Asia and Pacific	19	33.9
	Europe	11	19.6
	Australia	5	8.9
	Africa	2	3.6

	South America	1	1.8
	Total	***56***	***100.0***
Project types	Housing/ real estate	40	71.4
	Commercial/office projects (banks, hotels, castles, headquarters)	17	30.4
	Schools/education	15	26.8
	Industrial Projects	13	23.2
	Health/hospital projects	10	17.9
	Energy/ Power projects	9	16.1
	Transportation (roads, bridges, rails, tunnels etc)	5	8.9
	Prisons/ defence	3	5.4
	Water treatment plant/ Sewage projects	3	5.4
	Other (please specify)	6	10.7

Section two requested the experts to assess the significance of the CFFs for MiC projects based on a 5-point rating scale, where 1= very insignificant, 2= insignificant, 3= slightly significant, 4= significant, and 5=very significant. A rating scale was adopted because it is proven tool which allows researchers to capture the perception (and opinions) of expert in a quantitative way, supports robust statistical modelling (Ameyaw and Chan, 2015) and widely used in construction management research. Although 7-point and 9-point rating scales are also used in measuring the opinions of experts (Ameyaw and Chan, 2015; Osei-Kyei et al., 2017a), the current study employed a 5-point rating scale due to the following reasons. First, it is the most traditional scale used and commonly understood by many practitioners and academics. Second, it reduces the cognitive complexity associated with a wider scale and has been commonly used to investigate OSM management and implementation issues. For instance, a 5-point Likert scale has been used to examine the key constraints and mitigation strategies for prefabricated prefinished volumetric construction (Hwang et al., 2018a) and to evaluate the major barriers to offsite construction in China (Mao et al., 2014). The questionnaire was converted to an online-based survey form with aid of the *Survey Monkey* platform. A link to the online survey was generated and used to conduct the survey.

3.3 Expert participants and data collection approach

The survey respondents were experts (industry practitioners and academics) with relevant practical, knowledge and experiences in the implementation of MiC or OSM projects. The experts were selected based on the following criteria: (i) the expert should have substantial theoretical and research experience in MiC or OSM techniques; (ii) the expert should have sufficient hands-on experience and practical knowledge of the application of MiC or OSM techniques; and (iii) the expert should have been involved in at least one implemented MiC project (Ameyaw and Chan, 2015). The relevant experts were selected using the purposive sampling approach because there is no central global database for MiC or OSM experts.

The experts were identified from two main sources. Academic experts were identified from MiC or OSM research papers published in high impact construction management journals. OSM industry practitioners were identified from construction industry councils, institutes, associations and bodies throughout the world. After 11 months of tracing and searching, a total of 400 experts were identified for the study. Personalized emails were written to each of the experts, inviting them to participate in the survey. In each email, the link to the survey was attached and the expert was encouraged to complete the survey within 4weeks. After two rounds of reminders, a total of 56 valid responses from 18 countries (Table 2) were retrieved from the *Survey Monkey* online platform.

Although the sample was relatively small and arguably inadequate for quantitative analysis, it was deemed appropriate and suitable for analysis due to the following reasons: (i) the sample size exceeded the minimum of 30 valid responses required for the central limit theorem to make valid conclusions; (ii) the data represents the accumulated valuable experiences and knowledge of several MiC and OSM experts with years of research and/or industrial experience; (iii) smaller sample sizes are characteristic of online-based international questionnaire surveys (Ameyaw and Chan, 2015); and (iv) the sample was higher than those in similar international survey studies such as 27 (Sachs et al., 2007) and 42 (Osei-Kyei et al., 2017a).

3.4 Data analytical protocol

The collected data was analysed using IBM Statistical Package for the Social Sciences (IBM SPSS v.25). A structured approach was adopted in the analysis of the dataset. Figure 2 is a flowchart of the implemented data analysis methodology.

3.4.1 Pretesting of dataset

The Cronbach's Alpha statistic was used to measure the internal consistency of the grading scale and survey instrument adopted. The reliability analysis generated a high and acceptable Cronbach's Alpha of 0.849, which is higher than the minimum acceptable value of 0.7 (Tavakol and Dennick, 2011). The Shapiro – Wilk test was implemented to investigate normality of the dataset (Chou et al., 1998) and the results, as shown in Table 3 indicated that the dataset of the CFFs was not normally distributed at 95% confidence interval. A rank-based nonparametric test; the Kruskal – Wallis test was used to examine whether there are statistically significant differences in the responses of experts in terms of their working background. The Kruskal – Wallis test results in Table 3 showed that none of the CFFs were perceived statistically different and suggested that the responses of experts were unanimous and can be treated as a unified whole for analysis.

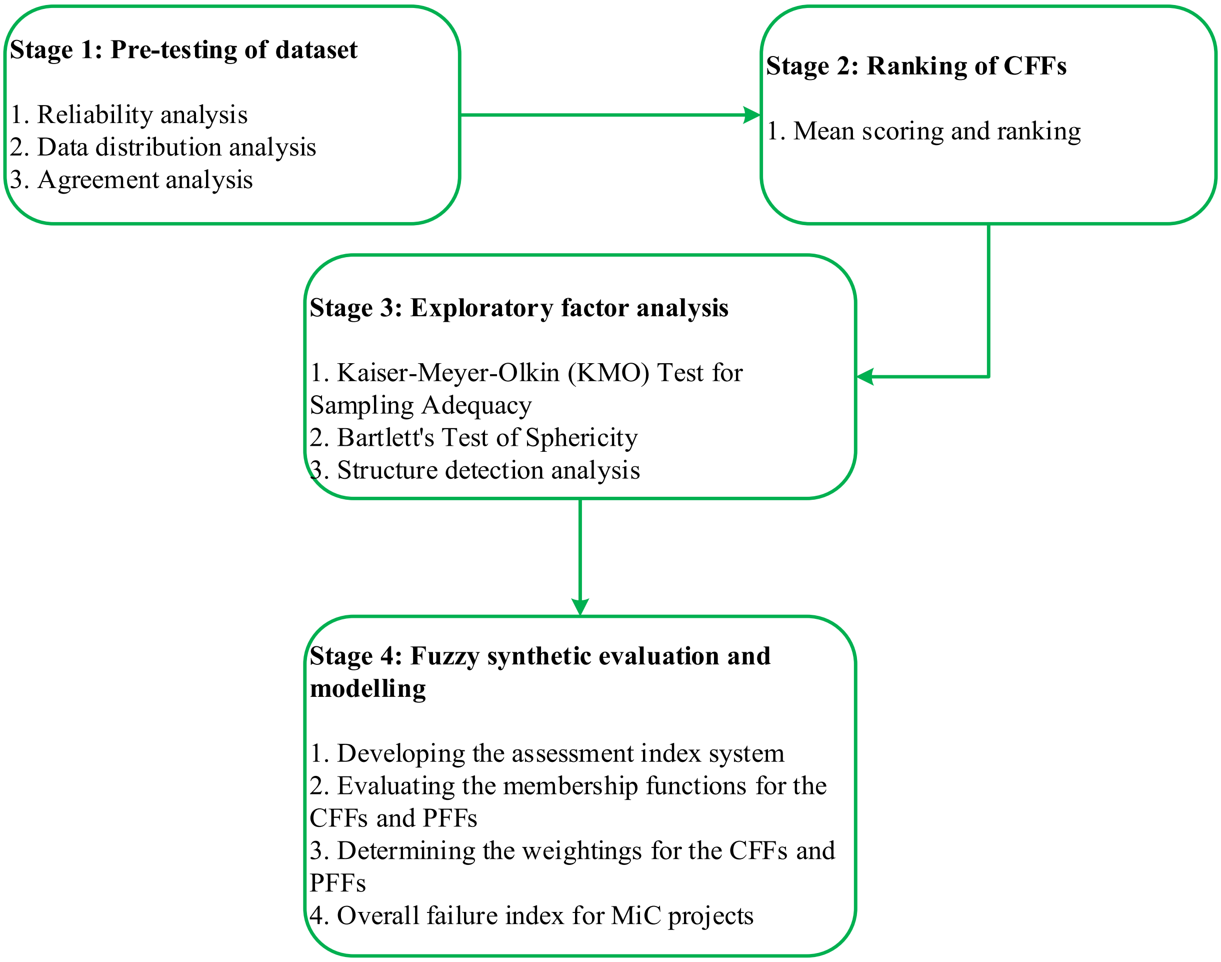

Figure 2. Flowchart of Data Analytical Protocol

3.4.2 Mean index estimations

The statistical mean is a standard tool for computing the central tendency of a dataset based on a grading scale (Hwang et al., 2018b). The mean aggregates the responses and produces an overall average quantitative profile of the relative importance of each CFF. The mean score (MS) for each CFF for MiC projects was computed as follows:

$$\text{MS } (\mu) = \frac{\sum(f \times s)}{N}, \quad 1 \leq \mu \leq 5 \qquad (1)$$

Where μ = mean score of a CFF; f = the number of ratings (i.e. 1-5) for a CFF; s = scores assigned to a CFF by the experts ranging from 1 to 5; and N = total number of responses obtained by a CFF. Table 3 shows the mean scores of all the CFFs. Although the cut off point or critical score of a Likert scale depends on the fuzzy linguistic variables assigned to each number on the scale, 3.50 is commonly used as the minimum threshold for a 5-point rating scale (Hwang et al., 2018a; Mao et al., 2014; Wuni and Shen, 2020b). On the 5-point rating scale used in this study, 3.0 was assigned 'slightly significant' and 4.0 was assigned 'significant'. Thus, factors with mean scores greater than 3.50 were closer to 'significant' than 'slightly significant' on the scale. For this, the conventional 3.50 was considered the minimum threshold mean value for determining the critical failure factors.

3.4.3 Exploratory factor analysis

The dataset was examined to ascertain its suitability for factor analysis. The factor to sample size ratio (1:3) of the current dataset did not meet the 1:5 (Lingard and Rowlinson, 2006) precondition for exploratory factor analysis. Indeed, this requirement has proven difficult to meet in existing studies (Ameyaw and Chan, 2015; Osei-Kyei et al., 2017b; Zafar et al., 2019) that conducted factor analysis. Thus, based on best practices, the study investigated other overriding preconditions for factor analysis. First, the internal consistency and validity of the survey instrument was measured using the Cronbach's Alpha. Results of the reliability analysis ($\alpha = 0.849$) indicated very good internal consistency in the responses and validity of the survey instrument. Second, results of the Kruskal – Wallis test showed no statistically significant differences between the responses of the experts, indicating that the dataset can be treated holistically for factor analysis (Chou et al., 1998). Third, the Kaiser-Meyer-Olkin Measure of Sampling Adequacy generated a test statistic of 0.697, which is within the acceptable range (Norusis, 2008). Fourth, the Bartlett's Test of Sphericity was significant ($p<0.000$) at 95% confidence interval with an approximate Chi-Square value of 542.246, indicating that the CFFs are significantly related and suitable for structure detection. Although there are other conditions which need to be satisfied (e.g. anti-image correlation) before conducting factor analysis, the four conditions have commonly formed the basis for factor analysis in previous studies (Osei-Kyei et al., 2017a). An exploratory factor analysis was implemented using Principal Component Analysis as the factor extraction method and Equamax with Kaiser Normalization as the factor rotation method. The rotation converged in 8 iterations and generated a 4 – factor solution of the CFFs, explaining about 72.34% of the total variance in the failure of MiC projects. Results of the factor analysis are shown in Table 4 and the factor groupings are referred to as principal failure factors (PFFs). Although a scree plot was required to determine the number of factors or principal components to be retained, it was not presented in the study due two main reasons. **First, the principal component**

analysis generated four components or factors, explaining about 72.34% of the total variance, a value significantly higher than the minimum threshold of 60 or 65% in the literature. The four principal components were few and manageable and the individual factors within each component were very much related. Second, the manuscript was already long and there was the need to eliminate any content which did not compromise the overall quality of the paper. This decision is consistent with the practice in existing studies in construction management (Mao et al., 2014; Osei-Kyei et al., 2017b; Zafar et al., 2019) which did not report scree plot in their exploratory factor analysis.

3.4.4 Fuzzy synthetic evaluation modelling of the CFFs and PFFs

The evaluation of the CFFs for MiC projects by the experts using linguistic variables such as *very insignificant* or *significant* are associated with uncertainties, biases, subjectivity, and fuzziness (Boussabaine, 2014). Fuzzy set theory is a useful tool for making objective assessment of the subjective responses (Sadiq and Rodriguez, 2004). It uses membership functions to quantify the degree to which an element belongs to a set (Zadeh, 1965) and fuzzy logic provides a natural framework for managing the imprecision and uncertainty within the responses of the experts (Zadeh, 1975). Fuzzy synthetic evaluation (FSE) analysis is a branch of fuzzy logic which provides a unique methodology for eliminating the fuzziness associated with evaluation of the CFFs and was implemented to model the CFFs for MiC projects. Based on Sadiq and Rodriguez (2004) and Ameyaw and Chan (2015), a 4-stage FSE protocol was implemented.

3.4.4.1 Developing the fuzzy evaluation index system

The exploratory factor analysis of the CFFs generated 4 PFFs, which constituted the first-level structure of the FSE index systems (Ameyaw and Chan, 2015). This first-level index system is expressed as $F = (f_1, f_2, f_3, f_4)$. Similarly, the CFFs (Table 4) within each PFF constitute the second-level index system, which is expressed as:

$f_1 = \{f_{11}, f_{12}, f_{13}, f_{14}, f_{15}, f_{16}, f_{17}, f_{18}\}$

$f_2 = \{f_{21}, f_{22}, f_{23}, f_{24}, f_{25}\}$

$f_3 = \{f_{31}, f_{32}, f_{33}, f_{34}\}$

$f_4 = \{f_{41}, f_{42}, f_{43}, f_{44}, f_{45}\}$

The index systems for PFF1, PFF2, PFF3, and PFF4 are denoted by f_1, f_2, f_3, and f_4, respectively. These four index systems constitute the input variables for the FSE modelling.

3.4.4.2 Determining the weightings of each CFF and PFF

Based on Lo (1999), the normalized mean approach was used to quantify the weights of the CFFs and PFFs because it is simple and consistent with the mean values generated for each CFF and PFF (Table 5). The weighting (w_i) for each CFF and PFF was computed through normalization of its mean score. Following Xu *et al.* (2010), the weight for each CFF and PFF was estimated as follows:

$$w_i = \frac{MS_i}{\sum_{i=1}^{n} MS_i}, 0 \leq w_i \leq 1, \text{ and } \sum_{i=1}^{n} w_i = 1 \quad (2)$$

Where w_i denotes the weighting of a CFF or PFF; and MS_i represents the mean score of a CFF or PFF. Table 5 shows the weightings of the CFFs and PFFs for MiC projects. The weighting function of a PFF is expressed as:

$$W_i = \{w_1, w_2, w_3, \ldots, w_n\} \quad (3)$$

Where W_i designates the weighting function of a PFF; and w_1 to w_n represent the weights of the various CFFs in a given PFF. The weighting functions of the PFFs formed the basis for computing their membership functions.

3.4.4.3 Computing the membership functions (MFs) of the CFFs and PFFs

A MF characterizes the fuzziness of an indicator in fuzzy set and quantifies the extent to which it belongs to a fuzzy set (Zadeh, 1975, 1965). The MFs uses grade alternatives to quantify the extent to which each CFF or PFF contributes to MiC project failure. Based on Ameyaw and Chan (2015), the grading alternatives for evaluating the CFFs can be expressed as a two-dimensional five-point grading scale as U = (1, 2, 3, 4, 5), where u1 = very insignificant, u2 = insignificant, u3 = slightly significant, u4 = significant, and u5 = very significant, for the degree of impact of the failure factors. Following Xu et al. (2010), the MF of a given CFF, tin is computed as follows:

$$MF_{t_{in}} = \frac{X_{1t_{in}}}{u_1} + \frac{X_{2t_{in}}}{u_2} + \frac{X_{3t_{in}}}{u_3} + \frac{X_{4t_{in}}}{u_4} + \frac{X_{5t_{in}}}{u_5} \quad (4)$$

where tin denotes the nth CFF in a given PFF, i (i = t1, t2, t3, t4, ..,tn); $MF_{t_{in}}$ represents the MF of a given CFF, tin; $X_{j_{t_{in}}}$ (j = 1, 2, 3, 4, 5) represents the percentage of the experts who rated j for a given CFF, tin, which denotes the degree of MF; the parameter $\frac{X_{j_{t_{in}}}}{u_i}$ measures the relation between $X_{j_{t_{in}}}$ and its grade alternative; and the plus (+) sign is a fuzzy notation instead of an addition. The MF of a given CFF ranges between [0,1] and the summation of $MF_{t_{in}}$ must be equal to 1. Using equation (4), the MF of a CFF, tin is expressed as:

$$\mathrm{MF}_{t_{in}} = \left(X_{1_{t_{in}}},\ X_{2_{t_{in}}},\ X_{3_{t_{in}}},\ X_{4_{t_{in}}},\ X_{5_{t_{in}}}\right) \quad (5)$$

However, the MF for a given PFF (fuzzy evaluation matrix, D_i) is computed as the product of its weighting function (equation 3) and fuzzy matrix (R_i). A fuzzy matrix (R_i) for a given PFF is developed using the MFs of its component CFFs. From equation (5), the fuzzy matrix for a given PFF is expressed as:

$$R_i = \begin{vmatrix} \mathrm{MF}_{t_{i1}} \\ \mathrm{MF}_{t_{i2}} \\ \mathrm{MF}_{t_{i3}} \\ \dots\dots \\ \mathrm{MF}_{t_{in}} \end{vmatrix} = \begin{vmatrix} X_{1_{t_{i1}}} & X_{2_{t_{i1}}} & X_{3_{t_{i1}}} & X_{4_{t_{i1}}} & X_{5_{t_{i1}}} \\ X_{1_{t_{i2}}} & X_{2_{t_{i2}}} & X_{3_{t_{i2}}} & X_{4_{t_{i2}}} & X_{5_{t_{i2}}} \\ X_{1_{t_{i3}}} & X_{2_{t_{i3}}} & X_{3_{t_{i3}}} & X_{4_{t_{i3}}} & X_{5_{t_{i3}}} \\ \dots\dots & \dots\dots & \dots\dots & \dots\dots & \dots\dots \\ X_{1_{t_{in}}} & X_{2_{t_{in}}} & X_{3_{t_{in}}} & X_{4_{t_{in}}} & X_{5_{t_{in}}} \end{vmatrix} \quad (6)$$

Given the weighting function of each PFF and the fuzzy matrix, MF (D_i) of a given PFF is computed as follows:

$$D_i = W_i \bullet R_i = (w_{i1}, w_{i2}, \dots, w_{in}) \bullet \begin{vmatrix} X_{1_{t_{i1}}} & X_{2_{t_{i1}}} & X_{3_{t_{i1}}} & X_{4_{t_{i1}}} & X_{5_{t_{i1}}} \\ X_{1_{t_{i2}}} & X_{2_{t_{i2}}} & X_{3_{t_{i2}}} & X_{4_{t_{i2}}} & X_{5_{t_{i2}}} \\ X_{1_{t_{i3}}} & X_{2_{t_{i3}}} & X_{3_{t_{i3}}} & X_{4_{t_{i3}}} & X_{5_{t_{i3}}} \\ \dots\dots & \dots\dots & \dots\dots & \dots\dots & \dots\dots \\ X_{1_{t_{in}}} & X_{2_{t_{in}}} & X_{3_{t_{in}}} & X_{4_{t_{in}}} & X_{5_{t_{in}}} \end{vmatrix} = (d_{i1}, d_{i2}, d_{i3}, \dots d_{in}) \quad (7)$$

Where d_{in} is the degree of membership of the grade alternative, f_i regarding a given PFF i; the symbol "•" is a fuzzy composite operator; and the rest of the parameters reserve their previous definitions.

3.4.4.4 Quantifying the impact of the PFFs for MiC projects

Given the MFs of the PFFs and the grade alternatives of the five-point rating scale, the impact levels of the PFFs for MiC projects can be quantified. The impact index of each PFF for MiC projects can be quantified as follows:

$$\text{Impact Index (II)} = \sum_{i=1}^{n} (D_i \times E_i) \quad (8)$$

Where; D_i denotes the MF of a given PFF and E_i represents the grade alternatives (1, 2, 3, 4, 5) of the 5-point rating scale.

4. Results of the data analysis

4.1 Mean score assessment and ranking of the CFFs for MiC projects

Mean scores, standard deviations, and rankings of the 22 CFFs for MiC projects are shown in Table 3. The mean scores together with the standard deviations indicate that CFF1 – inaccurate engineering specifications and late design freeze (3.96), CFF2 – limited fabricator experience and capabilities in modules design and production (3.91), CFF3 – poor working collaboration and infrequent communication among project participants (3.86), CFF4 –

supply chain disruptions and disturbances (3.80), and CFF5 – poor coordination of the fragmented supply chain segments (3.79) are the top five most significant factors causing MiC project failures.

Table 3. Mean Score Assessment of the CFFs for MiC Projects

Code	CFFs	Mean	SD	Rank	Shapiro - Wilk test (P-value)	Kruskal-Wallis test (p-value)
CFF1	Inaccurate engineering specifications and late design freeze	3.96	0.81	1	0.000	0.931
CFF2	Limited fabricator experience and capabilities in modules design and production	3.91	0.79	2	0.000	0.291
CFF3	Poor working collaboration and infrequent communication among project participants	3.86	0.80	3	0.000	0.534
CFF4	Supply chain disruptions and disturbances	3.80	0.90	4	0.000	0.627
CFF5	Poor coordination of the fragmented supply chain segments	3.79	0.76	5	0.000	0.736
CFF6	Unsuitability of design for MiC	3.79	0.97	5	0.000	0.834
CFF7	Non-involvement of key participants throughout the major stages of the project lifecycle	3.77	0.85	7	0.000	0.605
CFF8	Poor client understanding, receptivity and acceptance of MiC	3.77	1.03	7	0.000	0.900
CFF9	Planning and scheduling deficiencies	3.71	0.87	9	0.000	0.958
CFF10	Use of inexperienced workforce	3.71	0.91	9	0.000	0.874
CFF11	Non-engagement of key participants at the earliest stage of the project	3.70	0.89	11	0.000	0.816
CFF12	Significant dimensional variabilities and site-fit-reworks	3.68	0.96	12	0.000	0.393
CFF13	Limited skilled workforce, management and supervising team	3.68	0.99	12	0.000	0.697
CFF14	Late advice and consideration of MiC in the project	3.66	1.00	14	0.000	0.453
CFF15	Unavailability of sound local transport infrastructure and site equipment capabilities	3.63	0.96	15	0.000	0.504
CFF16	Unsupportive design layout and construction	3.61	0.98	16	0.000	0.752
CFF17	Unrealistic economic analysis and definition of MiC project scope	3.55	0.87	17	0.000	0.239
CFF18	Errors in modular connection on the site	3.54	1.35	18	0.000	0.099
CFF19	Poor coordination and integration of the conflicting interests of the relevant stakeholders	3.52	0.91	19	0.000	0.488
CFF20	Poor skills in coordinating on-site and off-site construction interfaces	3.52	1.01	19	0.000	0.559
CFF21	Use of unsuitable procurement system and contracting	3.46	0.87	21	0.000	1.000
CFF22	Ineffective stakeholder, supply chain and execution risk management	3.34	0.82	22	0.000	0.213

These CFFs should be given significant attention in the implementation of MiC projects. Except for CFF21 and CFF22, the mean scores of the remaining CFFs in Table 3 exceed the minimum threshold of 3.50, highlighting that these management areas are at least significant factors causing MiC project failure. The standard deviations in Table 3 measure how far the overall rating of a factor by the experts deviate from the associated mean score. Additionally, if two or more CFFs have the same mean score, the one with a lower standard deviation was assigned a higher rank (e.g. CFF7 & CFF8, CFF9 & CFF10, CFF12 & CFF13, and CFF19 & CFF20). The standard deviations helped to measure the consensus in the ratings of the experts. Although there are no benchmarks for the minimum and maximum standard deviations, smaller values are preferred to higher scores. For this reason, although CFF21 and CFF22 had mean scores less than 3.50, they were still discussed due to the closer proximity of their mean scores to 3.50 and the associated smaller standard deviations. Except for CFF8, CFF14, CFF18, and CFF20 with standard deviations above 1.0, the remaining CFFs had standard deviations less than 1.0, suggesting higher consensus among the experts.

4.2 Principal failure factors for MiC projects

CFFs are usually few, ranging from 5 to 8 (Freund, 1988). Thus, it is useful to organize the long lists of CFFs in Table 3 into a comprehensive framework for easy handling. Exploratory factor analysis of the CFFs generated 4 PFFs, as shown in Table 4. Although not reported in Table 4, the Cronbach's Alpha was computed for each principal component as a measure of construct reliability. The analysis generated Cronbach's Alpha values of 0.779, 0.705, 0.711, and 0.724 for the PFF1, PFF2, PFF3, and PFF4, respectively. Although moderate, these reliability indices are within acceptable range (Tavakol and Dennick, 2011).

Table 4. PFFs for MiC projects

Code	CFFs/PFFs	Factor loadings	Eigen-value	% of variance explained	Cum. % of variance explained
PFF1	**Poor stakeholder and supply chain management**		**8.911**	**40.505**	**40.505**
CFF21	Use of unsuitable procurement system and contracting	0.904			
CFF5	Poor coordination of the fragmented supply chain segments	0.858			
CFF9	Planning and scheduling deficiencies	0.812			
CFF19	Poor coordination and integration of the conflicting interests of the relevant stakeholders	0.784			
CFF3	Poor working collaboration and infrequent communication among project participants	0.769			
CFF22	Ineffective stakeholder, supply chain and execution risk management	0.649			
CFF7	Non-involvement of key participants throughout the major stages of the project lifecycle	0.649			
CFF4	Supply chain disruptions and disturbances	0.521			
PFF2	**Poor design and dimensional variability management**		**2.591**	**11.778**	**52.283**
CFF16	Unsupportive design layout and construction	0.809			
CFF18	Errors in modular connection on the site	0.789			

CFF6	Unsuitability of design for MiC	0.782			
CFF12	Significant dimensional variabilities and site-fit-reworks	0.643			
CFF1	Inaccurate engineering specifications and late design freeze	0.421			
PFF3	**Limited technical knowledge, capability and experience**		**2.480**	**11.270**	**63.553**
CFF13	Limited skilled workforce, management and supervising team	0.854			
CFF10	Use of inexperienced workforce	0.814			
CFF20	Poor skills in coordinating on-site and off-site construction interfaces	0.789			
CFF2	Limited fabricator experience and capabilities in component design and production	0.760			
PFF4	**Late commitment**		**1.933**	**8.788**	**72.341**
CFF15	Unavailability of sound local transport infrastructure and site equipment capabilities	0.730			
CFF17	Unrealistic economic analysis and definition of MiC project scope	0.698			
CFF14	Late advice and consideration of MiC in the project	0.638			
CFF8	Poor client understanding, receptivity and acceptance of MiC	0.557			
CFF11	Non-engagement of key participants at the earliest stage of the project	0.493			

The 4 PFFs explain about 72.34% of the total variance in the failure of MiC projects. The PFFs include poor stakeholder and supply chain management (PFF1), poor design and dimensional variability management (PFF2), limited technical knowledge, capability and experience (PFF3), and late commitment (PFF4). Clustering the 22 CFFs into 4 PFFs is useful because it provides: (i) a comprehensive framework which enables developers and project managers to efficiently allocate resources and focus on few management areas to reduce failure risks; and (ii) a systematic framework for quantifying the impact of each PPF and to identify those with the greatest contribution to MiC project failure (Ameyaw and Chan 2015).

4.3 Weightings of the CFFs and PFFs for MiC projects

The weightings of the CFFs and PFFs for MiC projects are shown in Table 5. The weight for each CFF or PFF was computed using equation (2). Given that the mean score of CFF3 is 3.86 (Table 5) and PFF1 contains 8 CFFs, the weight of CFF3 was computed as follows:

$$W_{CFF3} = \frac{3.86}{3.86 + 3.80 + 3.79 + 3.77 + 3.71 + 3.52 + 3.46 + 3.34} = \frac{3.86}{29.25} = 0.132$$

Using the same approach, the weightings of the remaining CFFs were computed. Considering that PPF4 has a total mean score of 18.31 (Table 5), its weighting was computed as follows:

$$W_{PFF4} = \frac{18.31}{29.25 + 18.58 + 14.82 + 18.31} = \frac{18.31}{80.96} = 0.226$$

Using the same approach, the weightings of the remaining PFFs were computed and shown in Table 5. Based on the weightings of the 4 PFFs, the ordered importance of PFFs include PPF1 (0.361), PFF2 (0.229), PPF4 (0.226), and PFF3 (0.183). However, the weightings vary directly with increasing number of CFFs (ceteris paribus) and thus, the weightings may only serve as a proxy composite indicator for ranking the PFFs for MiC projects.

Table 5. Weighted Scores of the CFFs and PFFs for MiC Projects

Code	CFFs/PFFs	Mean for CFF	Weightings for each CFF	Total Mean for each PFF	Weightings for each PFF
PFF1	**Poor stakeholder and supply chain management**			**29.25**	**0.361**
CFF3	Poor working collaboration and infrequent communication among project participants	3.86	0.132		
CFF4	Supply chain disruptions and disturbances	3.80	0.130		
CFF5	Poor coordination of the fragmented supply chain segments	3.79	0.130		
CFF7	Non-involvement of key participants throughout the major stages of the project lifecycle	3.77	0.129		
CFF9	Planning and scheduling deficiencies	3.71	0.127		
CFF19	Poor coordination and integration of the conflicting interests of the relevant stakeholders	3.52	0.120		
CFF21	Use of unsuitable procurement system and contracting	3.46	0.118		
CFF22	Ineffective stakeholder, supply chain and execution risk management	3.34	0.114		
PFF2	**Poor design and dimensional variability management**			**18.58**	**0.229**
CFF1	Inaccurate engineering specifications and late design freeze	3.96	0.213		
CFF6	Unsuitability of design for MiC	3.79	0.204		
CFF12	Significant dimensional variabilities and site-fit-reworks	3.68	0.198		
CFF16	Unsupportive design layout and construction	3.61	0.194		
CFF18	Errors in modular connection on the site	3.54	0.191		
PFF3	**Limited technical knowledge, capability and experience**			**14.82**	**0.183**
CFF2	Limited fabricator experience and capabilities in component design and production	3.91	0.264		
CFF10	Use of inexperienced workforce	3.71	0.250		
CFF13	Limited skilled workforce, management and supervising team	3.68	0.248		
CFF20	Poor skills in coordinating on-site and off-site construction interfaces	3.52	0.238		
PFF4	**Late commitment**			**18.31**	**0.226**
CFF8	Poor client understanding, receptivity and acceptance of MiC	3.77	0.206		
CFF11	Non-engagement of key participants at the earliest stage of the project	3.70	0.202		
CFF14	Late advice and consideration of MiC in the project	3.66	0.200		

CFF15	Unavailability of sound local transport infrastructure and site equipment capabilities	3.63	0.198
CFF17	Unrealistic economic analysis and definition of MiC project scope	3.55	0.194

4.4 MFs of the CFFs and PFFs for MiC projects

The MFs of the CFFs and PFFs for MiC projects are shown in Table 6. The MFs were computed from the percentage responses for each CFF and PFF. For example, 1.8% of the experts rated CFF6 as *very insignificant*, 5.4% rated CFF6 as *insignificant*, 32.1% rated CFF6 as *slightly significant*, 33.9% and 26.8% rated CFF6 as *significant* and *very significant*, respectively. Using equation (4), the MF of CFF6 was computed as follows:

$$\mathrm{MF}_{\mathrm{CFF6}} = \frac{0.018}{u_1} + \frac{0.054}{u_2} + \frac{0.321}{u_3} + \frac{0.339}{u_4} + \frac{0.268}{u_5}$$

Table 6. MFs of the CFFs and PFFs for MiC Projects

Code	CFFs/PFFs	W_i for CFFs	Membership Functions for CFFs	Membership Functions for PFFs
PFF1	**Poor stakeholder and supply chain management**			**(0.00, 0.09, 0.33, 0.42, 0.17)**
CFF3	Poor working collaboration and infrequent communication among project participants	0.132	(0.00, 0.04, 0.29, 0.46, 0.21)	
CFF4	Supply chain disruptions and disturbances	0.130	(0.00, 0.09, 0.25, 0.43, 0.23)	
CFF5	Poor coordination of the fragmented supply chain segments	0.130	(0.00, 0.04, 0.30, 0.50, 0.16)	
CFF7	Non-involvement of key participants throughout the major stages of the project lifecycle	0.129	(0.00, 0.09, 0.23, 0.50,0.18)	
CFF9	Planning and scheduling deficiencies	0.127	(0.00, 0.11, 0.27, 0.43, 0.20)	
CFF19	Poor coordination and integration of the conflicting interests of the relevant stakeholders	0.120	(0.00, 0.14, 0.34, 0.38, 0.14)	
CFF21	Use of unsuitable procurement system and contracting	0.118	(0.02, 0.07, 0.46, 0.32, 0.13)	
CFF22	Ineffective stakeholder, supply chain and execution risk management	0.114	(0.00, 0.13, 0.50, 0.29, 0.09)	
PFF2	**Poor design and dimensional variability management**			**(0.03, 0.09, 0.27, 0.35, 0.26)**
CFF1	Inaccurate engineering specifications and late design freeze	0.213	(0.00, 0.05, 0.18, 0.52, 0.25)	
CFF6	Unsuitability of design for MiC	0.204	(0.02, 0.05, 0.32, 0.34, 0.27)	
CFF12	Significant dimensional variabilities and site-fit-reworks	0.198	(0.00, 0.14, 0.27, 0.36, 0.23)	
CFF16	Unsupportive design layout and construction	0.194	(0.04, 0.05, 0.38, 0.34, 0.20)	
CFF18	Errors in modular connection on the site	0.191	(0.09, 0.16, 0.23, 0.18, 0.34)	
PFF3	**Limited technical knowledge, capability and experience**			**(0.01, 0.07, 0.33, 0.38, 0.21)**
CFF2	Limited fabricator experience and capabilities in component design and production	0.264	(0.00, 0.02, 0.30, 0.43, 0.25)	
CFF10	Use of inexperienced workforce	0.250	(0.00, 0.07, 0.34, 0.39, 0.20)	
CFF13	Limited skilled workforce, management and supervising team	0.248	(0.02, 0.09, 0.29, 0.41, 0.20)	

CFF20	Poor skills in coordinating on-site and off-site construction interfaces	0.238	(0.02, 0.13, 0.38, 0.29, 0.20)	
PFF4	**Late commitment**			**(0.01, 0.11, 0.28, 0.41, 0.19)**
CFF8	Poor client understanding, receptivity and acceptance of MiC	0.206	(0.04, 0.07, 0.23, 0.41, 0.25)	
CFF11	Non-engagement of key participants at the earliest stage of the project	0.202	(0.02, 0.04, 0.38, 0.38, 0.20)	
CFF14	Late advice and consideration of MiC in the project	0.200	(0.00, 0.18, 0.18, 0.45, 0.20)	
CFF15	Unavailability of sound local transport infrastructure and site equipment capabilities	0.198	(0.00, 0.14, 0.29, 0.38, 0.20)	
CFF17	Unrealistic economic analysis and definition of MiC project scope	0.194	(0.00, 0.13, 0.32, 0.43, 0.13)	

Alternatively, the MF of CFF6 is expressed as (0.02, 0.05, 0.32, 0.34, 0.27), as shown in Table 6. Using the same approach, the MFs of the remaining CFFs were computed. The MFs of the PFFs for MiC projects were computed from their weighting functions and fuzzy matrices. For example, the weighting function of PFF4 – late commitment (Table 5) and its fuzzy matrix (Table 6) can be expressed as:

$W_{PFF4} = (0.206, 0.202, 0.200, 0.198, 0.194)$

$$R_{PFF4} = \begin{vmatrix} MF_{CFF8} \\ MF_{CFF11} \\ MF_{CFF14} \\ MF_{CFF15} \\ MF_{CFF17} \end{vmatrix} = \begin{vmatrix} 0.04 & 0.07 & 0.23 & 0.41 & 0.25 \\ 0.02 & 0.04 & 0.38 & 0.38 & 0.20 \\ 0.00 & 0.18 & 0.18 & 0.45 & 0.20 \\ 0.00 & 0.14 & 0.29 & 0.38 & 0.20 \\ 0.00 & 0.13 & 0.32 & 0.43 & 0.13 \end{vmatrix}$$

Using equation (7), the MF of PPF4 was computed as follows:

$$MF_{PFF4} = D_{PFF4} = (0.206, 0.202, 0.200, 0.198, 0.194) \bullet \begin{vmatrix} 0.04 & 0.07 & 0.23 & 0.41 & 0.25 \\ 0.02 & 0.04 & 0.38 & 0.38 & 0.20 \\ 0.00 & 0.18 & 0.18 & 0.45 & 0.20 \\ 0.00 & 0.14 & 0.29 & 0.38 & 0.20 \\ 0.00 & 0.13 & 0.32 & 0.43 & 0.13 \end{vmatrix}$$

= (0.01, 0.11, 0.28, 0.41, 0.19)

Using the same approach, the MFs of the remaining PPFs for MiC projects were computed (Table 6) and formed the basis for quantifying their impact on the failure of MiC projects.

4.5 Impact levels of the PFFs for MiC projects

Using equation (8), the impact index of a PFF for MiC projects was computed from its MF and the grade alternatives as follows:

$II_{PFF1} = D_{PFF1} * E_1 = (0.00, 0.09, 0.33, 0.42, 0.17) * (1, 2, 3, 4, 5) = 3.665$ (3rd)

$II_{PFF2} = D_{PFF2} * E_2 = (0.03, 0.09, 0.27, 0.35, 0.26) * (1, 2, 3, 4, 5) = 3.717$ (1st)

$II_{PFF3} = D_{PFF3} * E_3 = (0.01, 0.07, 0.33, 0.38, 0.21) * (1, 2, 3, 4, 5) = 3.711$ (2nd)

$II_{PFF4} = D_{PFF4} * E_3 = (0.01, 0.11, 0.28, 0.41, 0.19) * (1, 2, 3, 4, 5) = 3.662$ (4th)

Results of the impact analysis indicate that all the 4 PFFs were assessed as significant to the failure of MiC projects because each scored an impact index exceeding 3.50 on the 5-point grading scale implemented. Based on the impact indices, the ordered significance of the PFFs include PFF2 (1st, 3.717), PPF3 (2nd, 3.711), PFF1 (3rd, 3.665), and PFF4 (4th, 3.662). The minimal differences in the impact levels between the 4 PFFs suggest that the experts unanimously evaluated the factors as equally significant to the failure of MiC projects. These PFFs are discussed in the next section.

5. Discussions of key findings

5.1 Poor design and dimensional variability management (PFF2)

Failure of MiC projects could often be traced to poor management and decision-making at the early stages of the project lifecycle (Hwang et al., 2018b; Murtaza et al., 1993). During the early stages, detailed drawings, functional specifications, criteria for success, and all major deliverables are planned. The experts rated poor design and dimensional variability management (PFF2) as the most significant PFF for MiC projects with a criticality index of 3.717. PFF2 explains about 11.78% of the total variance in the failure of MiC projects through 5 CFFs, comprising inaccurate engineering specifications and late design freeze, unsuitability of design for MiC, significant dimensional variabilities and site-fit-reworks, unsupportive design layout, and errors in modules connection on the site. Technically, there is zero tolerance for design changes in MiC after freezing and during the production of the modules because such modifications are difficult and extremely expensive to implement. MiC projects are associated with increasing inflexibility and limited opportunities for changes as the design progress to the final stages (Fraser et al., 2015). Inaccurate engineering specification in the detailed design translates into systemic risk in the production of modules, which are sources of significant dimensional variabilities between the manufacturing tolerances and the on-site tolerance (Enshassi et al., 2019). Shahtaheri et al. (2017) found that variabilities exceeding the allowable tolerance limit are responsible for poor quality of the final project and requirement for site-fit-reworks. When the error-laden design is used in the mass production of the modules, the error (s) is replicated in each component with negative implications on the quality of the assembled project (Lee and Kim, 2017; Shahtaheri et al., 2017).

Meeting the tighter schedules of MiC projects requires timely design freeze, production and transportation of the modules to the construction site for assembly (Wuni et al., 2019). Considering that the modules are often made-to-order, late design freeze delays the production of the modules and subsequently increases construction time (Bortolini et al., 2019). Further, Murtaza et al. (1993) noted that an MiC project might failed at the early stages prior to the production of the modules when the suitability of the project design for MiC is not ascertained. Although advancement in modular design and architecture makes possible for the conversion of traditional project design to a modular version (Modular Building Institute, 2017), the implementation of a design which is inconsistent with the principles of modularity and modularization will not leverage the full benefits of the MiC technology (Fraser et al., 2015). MiC projects are most suitable for projects with repetitive design layout. Thus, the cost, time, productivity, quality, and sustainability benefits of MiC may not be realized if the project is implemented with a design layout which is inconsistent the MiC project layout (Hwang et al., 2018a).

5.2 Limited technical knowledge, capability and experience (PFF3)

Although some few unskilled workforces may be required to handle delivery of materials to the point of use, technical knowledge and skills in MiC are required at all levels of the project delivery chain from the design to the use of advanced and precise modular production technology through to the use of powerful cranes to systematically assemble the modules on site (Fraser et al., 2015). The PFF3 as the second most important PFF for MiC projects with a criticality index of 3.711. PFF3 explains about 11.27% of the total variance in the failure of MiC projects through 4 CFFs, comprising limited fabricator experience and capabilities in component design and production, use of inexperienced workforce, limited skilled workforce, management and supervising team, and poor skills in coordinating the on-site and off-site construction interfaces. Project quality, productivity and success are directly linked to skills of the workforce (Egan, 1998) and so, technical skills gap and inadequate knowledge are preventing the realization of MiC project objectives (Fraser et al., 2015).

Effective and successful implementation of MiC projects requires adequate understanding of what constitutes value to the client, the conditions which favours the adoption of MiC, the stage in which MiC commitment must be considered, and the MiC project delivery process. MiC projects are co-created and thus, the different project participants must have adequate knowledge of the MiC value chain and high technical skills in the project stage in which they are involved (Fraser et al., 2015). The design team makes the first significant contribution or compromise to the realization of the project objectives because the final project reflects the design intensions. Where the design team has limited technical knowledge of the principles of design for: manufacture, assembly, productivity, logistics, waste reduction, sustainability, commissioning, maintenance, adaptability, flexibility, decommissioning and deconstruction, the success of the MiC project may be compromised right from the earliest stages of the project lifecycle. With the increasing circumstances where an initially rejected MiC project design is re-considered at a later stage due to tighter schedules (Modular Building Institute, 2017), the design team requires adequate technical knowledge and experience to adopt early design strategies which does not preclude a later incorporation of MiC into a traditional project (Fraser et al., 2015).

According to Blismas (2007), fabricators without technical skills and capabilities in the design and production of the modules constitute a CFF for MiC projects. Fabricators require skills in production engineering, module manufacturing, DfMA, and process efficiency. Thus, fabricators with limited experience and capabilities in module design and production could compromise the realization of planned objectives of the MiC project (Wuni et al., 2019). According to Fraser et al. (2015), inexperienced fabricators may be unable to effectively manage dimensional tolerances, the greater level of complexity and sophistication of the modules production systems and may struggle to cope with disruptions in the module production process.

Although the MiC delivery chain supports a streamlined and structured management, project management and supervising team without adequate technical knowledge and skills in DfMA, supply chain management, stakeholder management, project and systems integration, production engineering, process efficiency, timing, sequencing and scheduling are unable to effectively manage the interfaces between the onsite and offsite work packages associated with MiC projects (Fraser et al., 2015). A project team with these skills gaps and deficiencies may generate unnecessary delays, dimensional variabilities, and supply chain problems (Wuni et al., 2019). Fraser et al. (2015) also identified that onsite management and installation workforce without adequate on-site skills in handling of materials and large building service modules, assembly of modules, logistics, schedule management, material and equipment planning and safe working with heavy modules will be counterproductive to the productivity, safety, schedule and quality benefits of MiC projects.

5.3 Poor stakeholder and supply chain management (PFF1)

MiC projects are associated with several stakeholders with their unique value systems, goals, concerns and interests along the entire delivery chain (Newcombe, 2003; Wuni et al., 2019). Failure to identify and manage the needs and concerns of involved stakeholder has resulted in several project failures because they have the power, resources and capability to stop a project (Olander and Landin, 2005). Poor coordination and management of the design, production, transportation and on-site assembly stages of the MiC supply chains has resulted in significant project failures (Li et al., 2016). Thus, the experts rated PFF1 as the third most significant PFF for MiC projects with a criticality index of 3.665. PFF1 explains about 40.51% of the total variance in the failure of MiC projects through 8 CFFs, comprising poor working collaboration and infrequent communication among project participants, supply chain disruptions and disturbances, poor coordination of fragmented supply chain segments, non-involvement of key participants throughout the major stages of the project lifecycle, planning and scheduling deficiencies, poor coordination and integration of the conflicting interests of the relevant stakeholders, use of unsuitable procurement system, and ineffective management of stakeholder, supply chain and execution risks. The primary role of stakeholder management in MiC projects is to generate a good collaborative environment which helps to stabilize the interest, predictability, power and legitimacy of the involved stakeholders to ensure successful completion of the project (Newcombe, 2003). The primary role of supply chain management in MiC projects is to coordinate and manage disruptions/disturbances along the fragmented segments of the MiC supply chain to ensure smooth workflow and value creation. One significant CFF within PFF1 is the planning and scheduling deficiencies. Doloi (2013) concluded that planning and scheduling deficiencies constitute critical drivers of cost overrun and project failures in Australia. Some symptoms of planning deficiencies include inaccurate cost estimation, selection of unsuitable procurement strategies, failure to recognize the impact stakeholders and supply chain disruptions on project schedules, unrealistic schedules, inadequate work definition, and poorly defined project management controls (Baloi and Price, 2003). These planning deficiencies may compromise the effectiveness of subsequent stages of the MiC project lifecycle.

Effective stakeholder management requires stakeholder mapping, salience analysis, coordination, engagement and disengagement (Newcombe, 2003; Pascale et al., 2019). Two success factors for stakeholder management in MiC projects include reconciling conflicting stakeholder interests with project objectives and good working collaboration among project participants (Wuni and Shen, 2019a; Xue et al., 2018). Thus, poor working collaboration, infrequent communication among project participants, and poor coordination and integration of the conflicting interests of the relevant stakeholders are significant sources of disruptive controversies among stakeholders in MiC projects, with greater chances of stakeholder dissatisfaction (Mbachu and Nkado, 2006). Love et al.(1998) noted that poor communication, lack of involvement, lack of feedbacks and controversies are the most fundamental sources of stakeholder dissatisfaction in construction projects, aside the nonrealization of planned objectives. Generally, project and stakeholder characteristics are fundamental factors for selecting a building procurement system. The selected procurement system have implications for stakeholder role assignment, flow of communication between project members, and supply chain configuration (Love et al., 1998). The MiC project delivery chain involves linked segments which require a collaborative working environment. Thus, the use of an unsuitable procurement system constitutes a significant factor causing MiC project failure (Blismas, 2007). Supply chain disruptions and poor coordination of the fragmented segments are critical agents of poor supply chain performances in MiC projects (Li et al., 2016). There are several events along the MiC project delivery chain which could trigger systemic disruptions and disturbances. Considering that the MiC supply chain segments are linked, disruptions in upstream segments may significantly disrupts downstream segments, especially in conditions where the supply chain is not resilient.

5.4 Late commitment (PFF4)

Consideration and commitment to MiC during the early stages of the project design maximizes benefits and minimizes risks (Fraser et al., 2015). A decision to implement MiC in a project influences the choice of design, selection of a procurement system and supply chain arrangement. Thus, the experts rated PFF4 as the fourth most significant PFF for MiC projects with a criticality index of 3.662. PFF4 explains about 8.79% of the total variance in the failure of MiC projects through 5 CFFs, comprising poor client understanding, receptivity and acceptance of MiC, late involvement of module fabricators and suppliers in project lifecycle, late advice and consideration of MiC in a project, unavailability of sound transport infrastructure and site equipment capabilities, and unrealistic economic analysis and definition of MiC project scope. Late advice on design suitability and consideration of MiC in a project results in late commitment to the MiC technology. Adequate time is required to plan the MiC project delivery process, but late commitment provides very little or no time for extensive planning and scheduling. Poor client understanding and receptivity of MiC constitutes a driver of the late advice and consideration of MiC in a project (Blismas and Wakefield, 2009). Where project design implemented and procurement system selected are inconsistent with the MiC, realization of planned objectives becomes impossible.

Late consideration reduces flexibility because when the decision to implement MiC is made after the completion of an initial traditional design, interfaces and adequate zones are not usually accounted and provided (Fraser et al., 2015). In circumstances where the initially rejected modular solution is reconsidered at a later stage in the project, the previous design may be significantly inappropriate for off-site delivery (Fraser et al., 2015). One major consequence of the late consideration of MiC is the potential for non-involvement of fabricators and suppliers at the design stage of the MiC project. Late involvement of fabricators implies that their input and expertise are not accommodated within the design of the project. This reduces the buildability and constructability of the MiC project design, resulting in decreased productivity and significant losses (Building and Construction Authority, 2017). Unavailability of sound transport infrastructure and site equipment capabilities are significant factors causing MiC project failure (Hwang et al., 2018a). Sound transport infrastructure is required for timely delivery of the modules to site to support timely assembly. Although just-in-time delivery arrangement reduces the need for storage of the modules and facilitates timely delivery of the modules to the site, such arrangements still require sound transport infrastructure to facilitate smooth and uninterrupted mobility. Further, inadequate site equipment capability constitutes a significant source of schedule delays and cost overrun (Li et al., 2016).

6. Theoretical, practical, managerial and sustainability implications of the research

Empirical research is source of innovation, theoretical development and continuous improvement in industrial practice (Cohen et al., 2002). The robust and rigorous identification and modelling of the CFFs for MiC projects in the current study have useful theoretical, practical and wider sustainability implications. Overall, the study makes a unique contribution to the MiC or OSM project management body of knowledge through benchmarking the most aggressive villains that predicate MiC project failures.

Theoretically, the research constitutes the first exclusive assessment of the generic but recurring villains in MiC project failures, drawing on global experiences and lessons. From a theoretical lens, the output of the research contributes to the checklist of factors that predicate MiC or OSM project failures and may contribute to the development of the MiC critical failure factors theory. Additionally, the outcome of the research provides a sound basis for future research on the failure factors for MiC or OSM projects in any country. This is of relevance to academic, industry and OSM policy researchers.

In the context of practice and management, the identified and prioritized CFFs will serve as a guide and managerial support in the implementation of MiC or OSM projects. Although no case studies were used to validate the findings, the outcome draws on wealth of global experiences and lessons and thus, they may reflect the realities of MiC project failures. As such, the findings of the research may guide contractors, subcontractors, project managers, clients, engineers, developers, and government authorities in reducing or avoiding failure of MiC projects. These stakeholders and practitioners may improve project success by recognizing and planning against the CFFs for MiC projects. Considering the generic modelling in the current study, project managers may have to conduct bespoke studies to prioritize the CFFs for the specific MiC or OSM project to facilitate efficient allocation of the scarce resources. In the absence of any bespoke research for a given country or project, the research results will form a useful implementation guide because most of these factors may cut across OSM project types, stages, and jurisdictions.

In the context of cleaner production and sustainability, this research has useful potential positive implications. As MiC reduces construction waste (Jaillon et al., 2009), pollution, carbon emissions, energy consumption (Quale et al., 2012) and improves health and safety of construction workers (Blismas et al., 2006), realization of more successful MiC projects may contribute significantly to sustainability and the wider ecological civilization transition in the built environment. Considering that the CFFs can be tracked and avoided, one potential impact of the study is wider success in project delivery and a resulting significant contribution to cleaner production in the built environment.

7. Conclusions, contributions and limitations of the research

The application of MiC together with the associated supply chain arrangement leverages significant gains in construction project performance in terms of speed, budget, quality, productivity and sustainability. MiC is considered a cleaner and greener construction approach within the green building and sustainability paradigm shift in the construction industry and thus, its wider adoption will contribute immensely to the cleaner production transition in the built environment. However, several factors and conditions determine the success or failure of MiC projects. Whilst majority of existing treatises have focused on evaluating the critical success factors, this research modelled 22 management areas that must be deficient for MiC projects to fail. The research draws a structured questionnaire survey which requested international MiC experts to evaluate the relative significance of the CFFs for MiC projects on a 5-point rating scale. Using the quantitative data from the global MiC experts, this research has deconstructed the causes of MiC project failure into CFFs and PFFs. Although the findings may vary across regions, the most significant and consistent villains in MiC project failure, based on mean score analysis may include inaccurate engineering specifications and late design freeze, limited fabricator experience and capabilities in modules design and production, poor working collaboration and infrequent communication among project participants, supply chain disruptions and disturbances, and poor coordination of the fragmented supply chain segments. A structure detection analysis generated 4 PFFs, explaining about 72.34% of the total variance in MiC project failure. The complex web of CFFs for MiC projects were broken out into four broad thematic categories or PFFs: poor design and dimensional variability management, poor stakeholder and supply chain management, limited technical knowledge, capability and experience, and late commitment. An FSE modeling of the 4 PFFs generated criticality indices for each PFF exceeding 3.50 on a 5-point rating scale, indicating that that the experts rated all the 4 PFFs as significant factors causing MiC project failures. The inclusive findings of the research point to the significant role of all the key project participants to MiC project success or failure and have useful implications. Practically, the research has identified and prioritized the management areas that must go wrong for MiC projects to fail. Thus, the research provides a useful management-support to minimize failure risk and improve success rate. Theoretically, the study has established a generic checklist of the CFFs for MiC projects and contributes to the checklists of failure factors for construction projects. The outcome of research may be applicable to many MiC project types and territories because the research draws on global experiences and lessons to identify and rank the CFFs for MiC projects. The findings may form a useful basis for future studies on OSM project failures. However, some limitations of the research are worth noting. First, although adequate, the sample size was small and may affect generalizability of the results. Nevertheless, the research generated a framework of the CFFs for MiC projects which can be prioritized in any given context. Second, the research overlooks the sensitivity of the CFFs to varying industry climate, culture, policy, and infrastructure in the different economies. Particularly, the relative importance of the CFFs may be different in developing and developed countries. A future comparative study may unravel these differences. Nonetheless, such generalization is plausible and useful because it makes the results more relevant to other countries than the assessment of CFFs in a specific context. Third, no real case studies were used to validate the identified CFFs and may be considered in future research. Future research aims to collect more data to quantify the impact of the CFFs and model their interactions in a specific country. Real-world case studies shall be used to validate the current findings.

References

Ameyaw, E.E., Chan, A.P.C., 2015. Evaluation and ranking of risk factors in public-private partnership water supply projects in developing countries using fuzzy synthetic evaluation approach. Expert Syst. Appl. 42, 5102–5116. https://doi.org/10.1016/j.eswa.2015.02.041

Baloi, D., Price, A.D.F., 2003. Modelling global risk factors affecting construction cost performance. Int. J. Proj. Manag. 21, 261–269. https://doi.org/10.1016/S0263-7863(02)00017-0

Belassi, W., Tukel, O.I., 1996. A new framework for determining success/failure factors in projects. Int. J. Proj. Manag. 14, 141–151.

Bertram, N., Fuchs, S., Mischke, J., Palter, R., Strube, G., Woetzel, J., 2019. Modular construction: From projects to products. New York, United States.

Blismas, N.G., 2007. Off-site manufacture in Australia : Current state and future directions. Brisbane, AUstralia.

Blismas, N.G., Pasquire, C., Gibb, A.G.F., 2006. Benefit evaluation for off-site production in construction. Constr. Manag. Econ. 24, 121–130. https://doi.org/10.1080/01446190500184444

Blismas, N.G., Pendlebury, M., Gibb, A.G.F., Pasquire, C., 2005. Constraints to the use of Off-site production on construction projects. Archit. Eng. Des. Manag. 1, 153–162. https://doi.org/10.1080/17452007.2005.9684590

Blismas, N.G., Wakefield, R., 2009. Drivers, constraints and the future of offsite manufacture in Australia. Constr. Innov. 9, 72–83. https://doi.org/10.1108/14714170910931552

Bortolini, R., Formoso, C.T., Viana, D.D., 2019. Site logistics planning and control for engineer-to-order prefabricated building systems using BIM 4D modeling. Autom. Constr. 98, 248–264. https://doi.org/10.1016/j.autcon.2018.11.031

Boussabaine, A., 2014. Risk Pricing Strategies for Public-Private Partnership Projects, 1st ed. ed. John Wiley & Sons, Ltd, Oxford. https://doi.org/10.1111/j.1532-950X.1982.tb00672.x

Building and Construction Authority, 2017. Overview of Design for Manufacturing and Assembly (DFMA). Singapore.

Choi, J.O., O'Connor, J.T., Kim, T.W., 2016. Recipes for Cost and Schedule Successes in Industrial Modular Projects: Qualitative Comparative Analysis. J. Constr. Eng. Manag. 142, 04016055. https://doi.org/10.1061/(asce)co.1943-7862.0001171

Chou, Y.-M., Polansky, A.M., Mason, R.L., 1998. Transforming Non-Normal Data to Normality in Statistical Process Control. J. Qual. Technol. 30, 133–141. https://doi.org/10.1080/00224065.1998.11979832

Cohen, W.M., Nelson, R.R., Walsh, J.P., 2002. Links and Impacts: The Influence of Public Research on Industrial R&D. Manage. Sci. 48, 1–23. https://doi.org/10.1287/mnsc.48.1.1.14273

Darko, A., Chan, A.P.C., Owusu-Manu, D.G., Ameyaw, E.E., 2017. Drivers for implementing green building technologies: An international survey of experts. J. Clean. Prod. 145, 386–394. https://doi.org/10.1016/j.jclepro.2017.01.043

Doloi, H., 2013. Cost overruns and failure in project management: Understanding the roles of key stakeholders in construction projects. J. Constr. Eng. Manag. 139, 267–279. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000621

Egan, J., 1998. Rethinking construction: The Report of the Construction Task Force. https://doi.org/Construction Task Force. Uk Government

Enshassi, M.S.A., Walbridge, S., West, J.S., Haas, C.T., 2019. Integrated Risk Management Framework for Tolerance-Based Mitigation Strategy Decision Support in Modular Construction Projects. J. Manag. Eng. 35, 05019004. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000698

Fraser, N., Race, G.L., Kelly, R., Winstanley, A., Hancock, P., 2015. An Offsite Guide for the Building and Engineering Services Sector. Loughborough. https://doi.org/10.1680/mpal.13.00031

Freund, Y.P., 1988. Critical Success Factors. Plan. Rev. 16, 20–23. https://doi.org/10.1108/eb054225

Gibb, A.G.F., Isack, F., 2003. Re-engineering through pre-assembly: Client expectations and drivers. Build. Res. Inf. 31, 146–160. https://doi.org/10.1080/09613210302000

Gibb, A.G.F., Neale, R.H.., 1997. Management of prefabrication for complex cladding: Case study. J. Archit. Eng. 3, 60–69. https://doi.org/10.1061/(ASCE)1076-0431(1997)3:2(60)

Goodier, C., Gibb, A.G.F., 2007. Future opportunities for offsite in the UK. Constr. Manag. Econ. 25, 585–595. https://doi.org/10.1080/01446190601071821

Goodier, C., Gibb, A.G.F., Mancini, M., Turck, C., Gjepali, O., Daniels, E., 2019. Modularisation and offsite in engineering construction: an early decision-support tool. Proc. Inst. Civ. Eng. - Civ. Eng. 1–45. https://doi.org/10.1680/jcien.19.00015

Hsu, P.Y., Angeloudis, P., Aurisicchio, M., 2018. Optimal logistics planning for modular construction using two-stage stochastic programming. Autom. Constr. 94, 47–61. https://doi.org/10.1016/j.autcon.2018.05.029

Hwang, B.-G., Shan, M., Looi, K.-Y., 2018a. Key constraints and mitigation strategies for prefabricated prefinished volumetric construction. J. Clean. Prod. 183, 183–193. https://doi.org/10.1016/j.jclepro.2018.02.136

Hwang, B.-G., Shan, M., Looi, K.Y., 2018b. Knowledge-based decision support system for prefabricated prefinished volumetric construction. Autom. Constr. 94, 168–178. https://doi.org/10.1016/j.autcon.2018.06.016

Jaillon, L., Poon, C.S., Chiang, Y.H., 2009. Quantifying the waste reduction potential of using prefabrication in building construction in Hong Kong. Waste Manag. 29, 309–320. https://doi.org/10.1016/j.wasman.2008.02.015

Lee, J.S., Kim, Y.S., 2017. Analysis of cost-increasing risk factors in modular construction in Korea using FMEA. KSCE J. Civ. Eng. 21, 1999–2010. https://doi.org/10.1007/s12205-016-0194-1

Li, C.Z., Hong, J., Xue, F., Shen, G.Q., Xu, X., Mok, M.K., 2016. Schedule risks in prefabrication housing production in Hong Kong: a social network analysis. J. Clean. Prod. 134, 482–494. https://doi.org/10.1016/j.jclepro.2016.02.123

Li, C.Z., Shen, G.Q., Xue, F., Luo, L., Xu, X., Sommer, L., 2017. Schedule risk modeling in prefabrication housing production. J. Clean. Prod. 153, 692–706.

https://doi.org/10.1016/j.jclepro.2016.11.028
Li, L., Li, Z., Wu, G., Li, X., 2018. Critical success factors for project planning and control in prefabrication housing production: A China study. Sustain. 10, 1–17. https://doi.org/10.3390/su10030836
Lingard, H., Rowlinson, S., 2006. Letter to the Editor. Constr. Manag. Econ. 24, 1107–1109. https://doi.org/10.1080/01446190601001620
Lo, S.M., 1999. A fire safety assessment system for existing buildings. Fire Technol. 35, 131–152. https://doi.org/10.1023/A:1015463821818
Love, P.E.D., Skitmore, M., Earl, G., 1998. Selecting a suitable procurement method for a building project. Constr. Manag. Econ. 16, 221–233. https://doi.org/10.1080/014461998372501
Luo, L., Mao, C., Shen, L., Li, Z., 2015. Risk factors affecting practitioners' attitudes toward the implementation of an industrialized building system a case study from China. Eng. Constr. Archit. Manag. 22, 622–643. https://doi.org/10.1108/ECAM-04-2014-0048
Luo, L., Shen, G.Q., Xu, G., Liu, Y., Wang, Y., 2019. Stakeholder-associated Supply Chain Risks and Their Interactions in a Prefabricated Building Project : A Case Study in Hong Kong. J. Manag. Eng. 35, 1–14. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000675
Lyytinen, K., 1988. Expectation failure concept and systems analysts' view of information system failures: Results of an exploratory study. Inf. Manag. 14, 45–56. https://doi.org/10.1016/0378-7206(88)90066-3
Lyytinen, K., Hirschheim, R., 1987. Information systems failures - a survey and classification of the empirical literature. Oxford Surv. Inf. Technol. 4, 257–309.
Mao, C., Shen, Q., Pan, W., Ye, K., 2014. Major Barriers to Off-Site Construction: The Developer's Perspective in China. J. Manag. Eng. 31, 04014043. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000246
Mao, C., Shen, Q., Shen, L., Tang, L., 2013. Comparative study of greenhouse gas emissions between off-site prefabrication and conventional construction methods: Two case studies of residential projects. Energy Build. 66, 165–176. https://doi.org/10.1016/j.enbuild.2013.07.033
Mbachu, J., Nkado, R., 2006. Conceptual framework for assessment of client needs and satisfaction in the building development process. Constr. Manag. Econ. 24, 31–44. https://doi.org/10.1080/01446190500126866
McGraw Hill Construction, 2013. Safety Management in the Construction Industry: Identifying Risks and Reducing Accidents to Improve Site Productivity and Project ROI, Smart Market Report. Bedford, MA.
Modular Building Institute, 2017. Modular Advantage for the Commercial Modular Construction Industry: the Offsite Construction Issue. Canada.
Murtaza, M.B., Fisher, D.J., Skibniewski, M.J., 1993. Knowledgment-Based Approach to Modular Construction Decision Support. J. Constr. Eng. Manag. 119, 115–130.
Newcombe, R., 2003. From client to project stakeholders: A stakeholder mapping approach. Constr. Manag. Econ. 21, 841–848. https://doi.org/10.1080/0144619032000072137
Norusis, M.J., 2008. SPSS 16.0 Advanced Statistical Procedures Companion. Prentice-Hall, Upper Saddle River, NJ. https://doi.org/10.1080/02331889108802322

Olander, S., Landin, A., 2005. Evaluation of stakeholder influence in the implementation of construction projects. Int. J. Proj. Manag. 23, 321–328. https://doi.org/10.1016/j.ijproman.2005.02.002

Osei-Kyei, R., Chan, A.P.C., Ameyaw, E.E., 2017a. A fuzzy synthetic evaluation analysis of operational management critical success factors for public-private partnership infrastructure projects. Benchmarking An Int. J. 24, 2092–2112. https://doi.org/10.1108/BIJ-07-2016-0111

Osei-Kyei, R., Chan, A.P.C., Javed, A.A., Ameyaw, E.E., 2017b. Critical success criteria for public-private partnership projects: international experts' opinion. Int. J. Strateg. Prop. Manag. 21, 87–100. https://doi.org/10.3846/1648715X.2016.1246388

Pan, W., Hon, C.K., 2018. Modular integrated construction for high-rise buildings. Proc. Inst. Civ. Eng. - Munic. Eng. 1–12. https://doi.org/10.1680/jmuen.18.00028

Pan, W., Sidwell, R., 2011. Demystifying the cost barriers to offsite construction in the UK. Constr. Manag. Econ. 29, 1081–1099. https://doi.org/10.1080/01446193.2011.637938

Pascale, F., Pantzartzis, E., Krystallis, I., Price, A.D.F., 2019. Rationales and practices for dynamic stakeholder engagement and disengagement . Evidence from dementia-friendly health and social care environments. Constr. Manag. Econ. 0, 1–17. https://doi.org/10.1080/01446193.2019.1679383

Quale, J., Eckelman, M.J., Williams, K.W., Sloditskie, G., Zimmerman, J.B., 2012. Construction Matters Comparing Environmental Impacts of Building Modular and Conventional Homes in the United States. J. Ind. Ecol. 16, 243–253. https://doi.org/10.1111/j.1530-9290.2011.00424.x

Sachs, T., Tiong, R., Qing Wang, S., 2007. Analysis of political risks and opportunities in public private partnerships (PPP) in China and selected Asian countries: Survey results. Chinese Manag. Stud. 1, 126–148. https://doi.org/10.1108/17506140710758026

Sadiq, R., Rodriguez, M.J., 2004. Fuzzy synthetic evaluation of disinfection by-products - A risk-based indexing system. J. Environ. Manage. 73, 1–13. https://doi.org/10.1016/j.jenvman.2004.04.014

Sanvido, V., Grobler, F., Parfitt, K., Guvenis, M., Coyle, M., 1992. Critical Success Factors for Construction Projects. J. Constr. Eng. Manag. 118, 94–111.

Shahtaheri, Y., Rausch, C., West, J., Haas, C., Nahangi, M., 2017. Managing risk in modular construction using dimensional and geometric tolerance strategies. Autom. Constr. 83, 303–315. https://doi.org/10.1016/j.autcon.2017.03.011

Smith, R.E., 2016. Off-Site and Modular Construction Explained [WWW Document]. Natl. Inst. Build. Sci. URL https://www.wbdg.org/resources/site-and-modular-construction-explained (accessed 11.11.18).

Tam, V.W.Y., Tam, C.M., Ng, W.C.Y., 2007a. On prefabrication implementation for different project types and procurement methods in Hong Kong. J. Eng. Des. Technol. 5, 68–80. https://doi.org/10.1108/17260530710746614

Tam, V.W.Y., Tam, C.M., Zeng, S.X., Ng, W.C.Y., 2007b. Towards adoption of prefabrication in construction. Build. Environ. 42, 3642–3654. https://doi.org/10.1016/j.buildenv.2006.10.003

Tavakol, M., Dennick, R., 2011. Making sense of Cronbach's alpha. Int. J. Med. Educ. 2, 53–

55. https://doi.org/10.5116/ijme.4dfb.8dfd
Wang, Z., Hu, H., Gong, J., 2018a. Simulation based multiple disturbances evaluation in the precast supply chain for improved disturbance prevention. J. Clean. Prod. 177, 232–244. https://doi.org/10.1016/j.jclepro.2017.12.188
Wang, Z., Hu, H., Gong, J., 2018b. Framework for modeling operational uncertainty to optimize offsite production scheduling of precast components. Autom. Constr. 86, 69–80. https://doi.org/10.1016/j.autcon.2017.10.026
Wuni, I.Y., Shen, G.Q., 2020a. Barriers to the adoption of modular integrated construction : Systematic review and meta-analysis , integrated conceptual framework , and strategies. J. Clean. Prod. 249, 119347. https://doi.org/10.1016/j.jclepro.2019.119347
Wuni, I.Y., Shen, G.Q., 2020b. Critical success factors for management of the early stages of prefabricated prefinished volumetric construction project life cycle. Eng. Constr. Archit. Manag. 1–15. https://doi.org/10.1108/ECAM-10-2019-0534
Wuni, I.Y., Shen, G.Q., 2019a. Critical success factors for modular integrated construction projects: a review. Build. Res. Inf. Inf. 0, 1–22. https://doi.org/10.1080/09613218.2019.1669009
Wuni, I.Y., Shen, G.Q., 2019b. Towards a Decision Support for Modular Integrated Construction : An Integrative Review of the Primary Decision-Making Factors. Int. J. Constr. Manag. 1–20. https://doi.org/10.1080/15623599.2019.1668633
Wuni, I.Y., Shen, G.Q., Hwang, B., 2020. Risks of modular integrated construction : A review and future research directions. Front. Eng. Manag. 7, 63–80. https://doi.org/10.1007/s42524-019-0059-7
Wuni, I.Y., Shen, G.Q., Mahmud, A.T., 2019. Critical risk factors in the application of modular integrated construction : a systematic review. Int. J. Constr. Manag. 1–15. https://doi.org/10.1080/15623599.2019.1613212
Xu, Y., Yeung, J.F.Y., Chan, A.P.C., Chan, D.W.M., Wang, S.Q., Ke, Y., 2010. Developing a risk assessment model for PPP projects in China-A fuzzy synthetic evaluation approach. Autom. Constr. 19, 929–943. https://doi.org/10.1016/j.autcon.2010.06.006
Xue, H., Zhang, S., Su, Y., Wu, Z., Yang, R.J., 2018. Effect of stakeholder collaborative management on off-site construction cost performance. J. Clean. Prod. 184, 490–502. https://doi.org/10.1016/j.jclepro.2018.02.258
Yeo, K.T., 2002. Critical failure factors in information system projects. Int. J. Proj. Manag. 20, 241–246. https://doi.org/10.1016/S0263-7863(01)00075-8
Zadeh, L.A., 1975. The concept of a linguistic variable and its application to approximate reasoning—II. Inf. Sci. (Ny). 8, 199–249. https://doi.org/10.1016/0020-0255(75)90036-5
Zadeh, L.A., 1965. Fuzzy Sets. Inf. Control 8, 338–353. https://doi.org/10.1016/S0019-9958(65)90241-X
Zafar, I., Wuni, I.Y., Shen, G.Q., Ahmed, S., Yousaf, T., 2019. A fuzzy synthetic evaluation analysis of time overrun risk factors in highway projects of terrorism-affected countries: the case of Pakistan. Int. J. Constr. Manag. 0, 1–19. https://doi.org/10.1080/15623599.2019.1647634