# Modelling the critical risk factors for modular integrated construction projects

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## Abstract

For many types of projects, modular integrated construction (MiC) is increasingly becoming a preferred method of construction. However, MiC projects are associated with unique risk factors different from those of the traditional construction projects. Thus, it is imperative to conduct a bespoke assessment of the risk factors for MiC projects. This research modelled 29 critical risk factors (CRFs) associated with MiC projects. Quantitative data on the relative significance of CRFs were collected from international MiC experts using structured questionnaires. A principal component analysis generated 4 principal risk factors (PRFs) for MiC projects comprising stakeholder and supply chain risks, design and capabilities risks, financing risks, and regulatory risks. A fuzzy synthetic modelling of the CRFs revealed that the 4 PRFs were significant but with varied impact on MiC projects. This research constitutes the first exclusive quantitative modelling of MiC risk factors with useful practical and theoretical implications. Practically, the research has identified and prioritized the CRFs associated with MiC projects and may serve as a risk evaluation decision support in MiC project planning and implementation. Theoretically, the results contribute to the checklists of CRFs for MiC projects which may form the basis for future studies on the risks of MiC projects.

**Keywords**: fuzzy synthetic evaluation; modular integrated construction; risk analysis; risk factors

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## Introduction

During the end of the 20th Century, the Egan (1998) Report demonstrated that the cost, time, quality, productivity, customer satisfaction, and environmental performance of projects engineered from the traditional stick-built construction (TSC) approach were falling short of desired requirement and sustainability indicators. These ill-performances were traced to the processes and end-products of the TSC approach. Off-site production (OSP) was put forward to address the shortfalls in the construction sector (Goulding *et al.* 2015). Modular integrated construction (MiC) is a disruptively-innovative OSP business model where prefinished volumetric modules (building components) are engineered in an off-site manufacturing plant, trucked to the job-site in section, set in place with cranes, and systematically installed to generate a complete building (Wuni and Shen 2019a, 2019b, 2020).

Where circumstances merit, and favourable conditions prevail, the effective implementation of MiC shortens construction time, improves working environment & site safety, results in high construction quality, reduces construction dust & noise nuisance, minimizes construction waste, improves construction waste management, and improves management of the construction process (Construction Industry Council 2018). However, the disruptive nature of the processes involved in MiC engenders unique events and conditions which could compromise the success of its projects. As a result, MiC is associated with several risk events and factors. For instance, late design freeze, schedule delays, and components' installation errors could be counterproductive to the widely reported time and quality benefits of MiC (Velamat 2012, Wuni *et al.* 2019). Poor coordination and management of downstream segments of the MiC supply chain could significantly compromise upstream supply chain events (Wuni and Shen 2019c). Poor coordination of cross-border transportation of modules could significantly increase construction cost (Pan and Hon 2018).

Considering that risk abound in MiC projects, effective management of the associated risks constitutes a critical success factor (Choi *et al.* 2016). However, risk management involves several stages, including risk identification, evaluation, prioritization, minimization, monitoring, and control (Project Management Institute 2017). The first three stages are critical because risks events are numerous in MiC projects, but not all the risk factors are critical. Again, resources are limited, which instructs the need to identify, assess and highlight the critical risk factors to be managed since they constitute the greatest threat to project success. However, existing MiC risks studies have been region-specific and primarily focused on schedule risks (Li *et al.* 2016, Li, Hong, *et al.* 2018), stakeholder risks (Luo *et al.* 2015, 2019), cost and investment risk factors (Li *et al.* 2013), risks of work-related musculoskeletal disorders (Kim *et al.* 2011, 2012) and risk of dimensional and geometric variabilities (Shahtaheri *et al.* 2017, Enshassi *et al.* 2019).

As a result, there is no existing study which has identified, evaluated, and prioritized risk factors in the application of MiC, drawing on international lessons and experiences. Therefore, this research conducts a quantitative assessment and modelling of the risk factors associated with the implementation of MiC projects. To achieve this, the following specific research questions warrant critical consideration:

*RQ1.* What are the critical risks factors associated with MiC projects?

*RQ2.* How can these critical risks factors be quantitatively assessed?

This paper is situated within a broader research project which seeks to develop a best practice framework for implementing MiC projects. The output of the quantitative evaluation and benchmarking of the risk factors have practical and theoretical implications. Theoretically, the research will establish the first generalized risk register for MiC projects and contributes to the theoretical checklists of risk factors associated with the technology. Practically, the research will highlight the critical risk factors that should be prioritized in MiC projects implementation to improve success.

### ***Point of departure***

Prior researches recognized the existence of risk factors in the implementation of MiC projects. Li et al. (2013) identified and assessed the impacts of risk factors on the cost and time performances of MiC projects in Canada using Analytical Hierarchy Process and Simulation. This study was useful but focused solely on the factors which affect time and cost of MiC projects in the context of Canada. The region-specific and narrow nature of the risk factors renders the study less useful to other countries with different construction climates and dynamics. Luo et al. (2015) identified and evaluated the risk factors that inhibit the adoption of MiC in China. Although useful, this study focused on the risk barriers to the adoption of MiC rather than the risk factors associated with the implementation of MiC projects. Again, the region-specific nature of the study renders it less useful to countries with different construction climates and industry dynamics.

Similarly, Li et al. (2016) assessed the schedule risks of residential MiC projects in Hong Kong using social network analysis whereas Li et al. (2017) modelled the schedule risk of residential MiC in the context of Hong Kong using systems dynamics. These studies were robust and useful, but they constituted scoping assessments of the risks associated with MiC projects. Subsequently, Li et al. (2018) modelled the schedule risk events in MiC projects using a hybrid of systems dynamics and discrete event simulation whereas Lee and Kim (2017) evaluated the risk factors that account for cost increase in MiC projects in Korea. These studies were scoping in nature and conducted in the context of Hong Kong and Korea, respectively. This limits the applicability of their results in other contexts since they did draw on international experts' opinions and data.

Luo et al. (2019) recently examined the stakeholder risks associated with MiC projects and explored the interactions of the risk events. However, it was conducted in the context of Hong Kong. More recently, Wuni et al. (2019) conducted a systematic review of studies on the risks of MiC and established a theoretical checklist of the risk factors associated with MiC Projects. However, the factors were ranked using the frequency of occurrences rather than the experiences and knowledge of international experts. Therefore, existing MiC risks literature do not include an empirical assessment of the generic risk factors associated with the implementation of MiC and drawing on the opinions of international experts. Thus, this research makes a unique contribution to the extant literature and constitutes a natural extension of the works of Wuni et al. (2019) through a quantitative evaluation of the critical risk factors associated with the implementation of MiC projects.

## Modular integrated construction

MiC is a disruptively-innovative construction approach that changes the way projects are planned, designed, engineered, constructed, and management in the construction engineering and management (CEM) domain. The Construction Industry Council (2018) defined MiC as an innovative construction technology where “free-standing integrated modules (completed with finishes, fixtures, and fittings) are manufactured and assembled in a factory", transported to the jobsite in sections and finally installed to generate liveable space. The prefabricated prefinished volumetric modules are manufactured in a workshop, partly assembled in the factory and then trucked in sections to the construction for final installation (Wuni *et al.* 2019). This makes the business model of MiC unique and individuates it from the traditional construction approach. MiC draws primarily on the concepts of modularity, modularization, lean production, and Design for Manufacture and Assembly, DfMA (Construction Industry Council 2018, Pan and Hon 2018).

The construction process involves distinct but interdependent stages of project design, statutory approvals, manufacturing of the modules, transportation of the modules to site, and on-site installation of the modules (Construction Industry Council 2018). The modules are designed based on local codes and engineering specifications (Hwang *et al.* 2018b). This stage often requires the early engagement of module fabricator, supplier, local contractor, and the client (Construction Industry Council 2018). This facilitates early completion and freezing of the design for subsequent stages to commence. Thus, late design freeze becomes a source of risks in the MiC supply chain (Wuni *et al.* 2019). The statutory approval stage is required to ensure that the design complies with building codes and regulations.

During the production stage, Hwang et al. (2018) noted that the fabrication method must be an accredited one to reduce dimensional and geometric variabilities. Before mass production, mock-ups, and prototypes of each type of modular component are fabricated, inspected, and tested (Construction Industry Council 2018). Trial assembly involving stacking of the modules is conducted in the factory to ascertain the ease of assembly at the job site. Since this stage proceeds the statutory approval, construction trades such as piling, foundation works, and external underground utility works are concurrently executed on the job-site. This shortens the construction time in MiC projects (Wuni *et al.* 2019). The modules are produced based on transport restrictions regarding masses and sizes. The produced modules may be transported to the job-site directly for installation, or they may be stored in a temporary location. The latter is known as buffering.

Finally, the modules are set in place with cranes and joined together to form the structure. Once the modules are firmly stacked together to form the volumetric units, both temporary and permanent waterproofing are executed. The prefinished volumetric modules are connected to other modules to form the modular building. The products of these processes are considered as industrialized building systems where the same design details and engineering specification could result in the construction of highly diversified and individualized buildings which can meet the requirements of different clients and inhabitants (Richard 2005). These building systems are flexible, demountable, and industrialized (Richard 2006) and can meet the multigenerational housing requirement. According to the Construction Industry Council (2018), the three forms of

MiC include reinforced concrete modules, steel frame modules, and hybrid modules based on construction materials.

However, some critical processes must be given due consideration in the supply chain of MiC. First, allowance and forgivable tolerance levels must be duly considered in the design and production of modules. This is because dimensional and geometric variabilities may trigger expensive rectification of errors and site-fit reworks (Shahtaheri *et al.* 2017). Second, the modules are often designed to be used specifically in an MiC project. Thus, the quantities of each type of module must precisely match the total of that module required to complete the project. This is because the inventory must return to zero on completion of the project to avoid wastage. Third, in case there will be an upstream supply of the modules for hedging, enough storage space must be created on-site or close to the site to temporarily accommodate the modules. The hedging is quite crucial because shortage of the modular components could halt the entire installation process and increase the cost of hired equipment and machinery (Wuni and Shen 2019c, Wuni *et al.* 2019). These and other critical events must be carefully considered because the impact of their (mis) occurrence could be counterproductive to the benefits of MiC projects.

## Research design and approach

This section describes the systematic procedures and techniques deployed to investigate the research problem. The study is situated within a positivist paradigm and adopts a quantitative research design to identify and assess the risk factors in the implementation of MiC projects. The research paradigm and design adopted instructs the use of quantitative data and analytical tools. Figure 1 shows the methodological framework of the research.

### *Prior literature and pilot study*

Before the questionnaire survey, the research developed risk factor register to be used to conduct the survey. Although a comprehensive review of the literature and content analysis is required to establish a checklist of the risk factors, the research constitutes an extension of the recent works of Wuni et al. (2019). The researchers conducted a systematic review of the extant literature on the risks of MiC and establish a generic list of risk factors for MiC projects. The current study adopted the checklists and conducted a pilot survey to ascertain their relevance to the different regions around the world. Three experts with rich industrial and research experience in MiC from Hong Kong and Australia were asked to examine the checklist to validate their relevance. The experts confirmed the adequacy and relevance of the risk factors to many MiC project types and territories. Table 1 shows the 29 risk factors used to conduct the survey.

**Table 1**. Risk factors in the implementation of MiC projects (Wuni *et al.* 2019)

| Serial No. | Risk factors |
|---|---|
| RF1 | Stakeholder fragmentation and management complexity |
| RF2 | Higher initial capital cost |
| RF3 | Poor supply chain integration and disturbances |
| RF4 | Delays in delivery of modules to the site |
| RF5 | Poor government support and regulations |
| RF6 | Lack of MiC design codes and standards |
| RF7 | Defective design and change order |
| RF8 | Supply chain information gap and inconsistency |
| RF9 | Inefficient scheduling |
| RF10 | Limited MiC expertise and experience |
| RF11 | Shortage of modular components |
| RF12 | Complex interfacing between systems |
| RF13 | Weather disruptions and force majeure |
| RF14 | Transportation restrictions |
| RF15 | Inexperience of contractors in MiC |
| RF16 | Specialist skilled labor requirement |
| RF17 | Modular installation errors, complex rectifications and reworks |
| RF18 | Poor cooperation and communication among project participants |
| RF19 | Modular design complexity |
| RF20 | Unsupportive planning and building regulations |
| RF21 | Limited capacity of modular manufacturers/suppliers |
| RF22 | Manual handling of heavy modules |
| RF23 | Absence of standardized modules |
| RF24 | Unable to freeze design early |
| RF25 | Higher prices of modules |
| RF26 | Diseconomies of scale and longer break-even period |
| RF27 | Modular production system failure |
| RF28 | Lack of best management practices |
| RF29 | Geometric and dimensional intolerances |

### *Survey approach and sample of participants*

Based on the precedents of Osei-Kyei et al. (2017), an international expert survey approach was adopted. This instructed the adoption of a quantitative research instrument and hence, the use of a questionnaire. The research relied solely on questionnaires due to the following reasons. (i) The quantitative evaluation of the risk factors required numerical data based on the opinions of international experts. Structured questionnaires are used to collect quantitative data using closed-ended questions and have been relied upon in previous studies to collect quantitative data (Zhang 2005, Sachs *et al.* 2007, Osei-Kyei *et al.* 2017). (ii) Questionnaires are known to many CEM researchers and industry practitioners, and hence, it can generate more reliable results (Wuni *et al.* 2019). (iii) Questionnaires can generate an adequate amount of data within a short period and can be considered as the cheapest survey instrument in terms of time and resources. Thus, following the precedents of international surveys, questionnaires were very appropriate for this study.

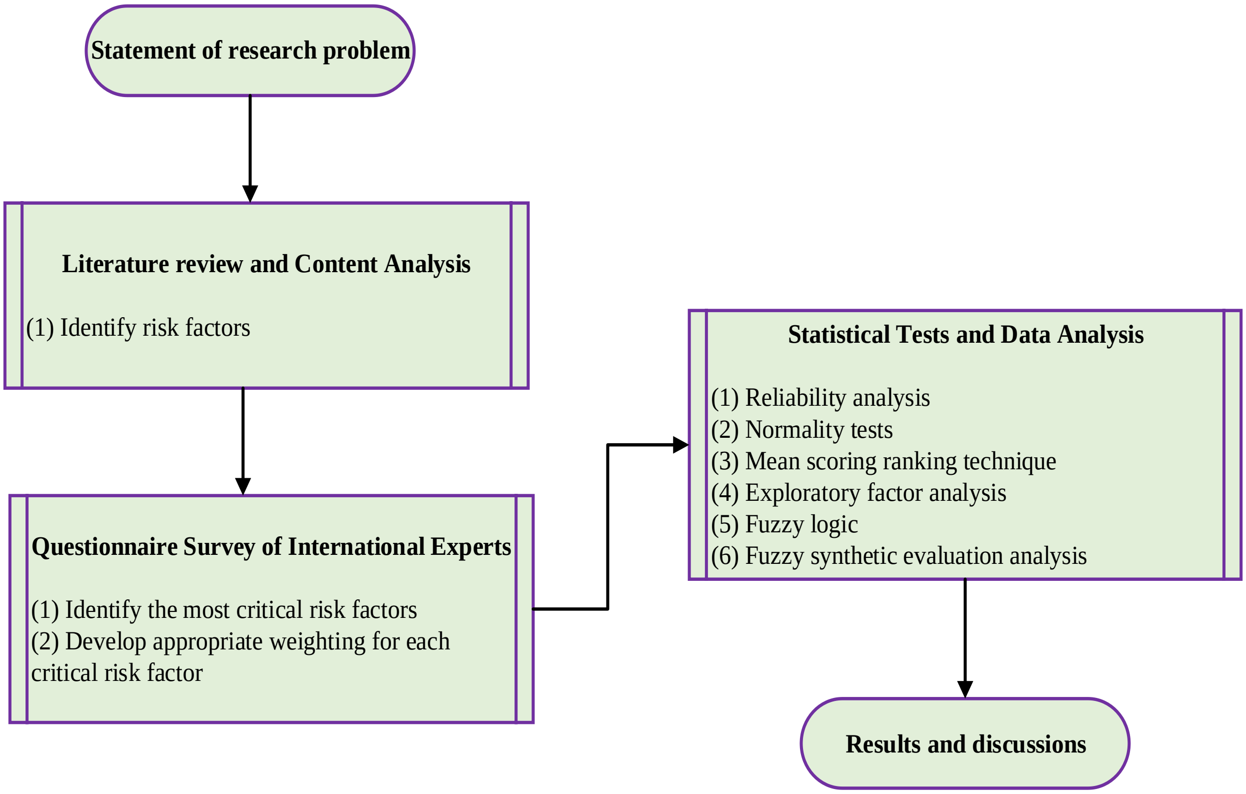

**Figure 1**. Methodological framework of the research

The study targeted MiC (including modular and off-site construction) experts in academia and industry. Considering that there is no central database for these experts, random sampling was practically inappropriate. As a result, the purposive and snowballing sampling techniques were adopted. The purposive sampling technique facilitated the collection of data from experts who had substantial and industry experience in MiC projects. In the context of the snowballing technique, experts were invited to respond to the questions and recommend other experts who have substantial experience in MiC projects. The experts were selected based on the following criteria. (i) The expert should have extensive theoretical and practical knowledge of MiC or similar models such as modular construction, prefabrication, industrialized building systems, or prefabricated prefinished volumetric construction. (ii) The experts should have detailed knowledge of the processes involved in MiC project delivery. (iii) The expert should have been involved in at least one MiC project (Osei-Kyei *et al.* 2017).

Given these criteria, the researchers collected contact information of MiC researchers from published articles in reputable journals and industry experts from reputable construction industry councils' websites. In all, 400 experts were invited to complete the online survey. The questionnaire requested the experts to evaluate the criticality of the risk factors on a 5-point grading scale; 1 = Least critical, 2 = Fairly critical, 3 = Critical, 4 = Very critical, and 5 = Extremely critical. These linguistic variables and grading continuum are appropriate for evaluating the risk factors based on fuzzy logic. After several reminders, a total sample of 56 responses was collected and was deemed adequate for analysis. Although small, such sample sizes are characteristic of web-based international surveys in CEM research. Indeed, the sample size compares favourably against similar international surveys such as 46 (Zhang 2005), 42 (Osei-Kyei *et al.* 2017), and 29 (Sachs *et al.* 2007).

### ***Statistical analysis and data pretesting***

Statistical analyses were executed on the data to ascertain its reliability and suitability for adopted methods of data analysis in the research. The analysis was conducted using the Statistical Package for the Social Sciences (SPSS v.25). A reliability test of internal consistency in the survey instrument was conducted using the Cronbach's Alpha. Based on this indicator, the statistical reliability of the dataset ranges from 0 to 1, where an Alpha value closer to 1 signals stronger reliability of the dataset and a value closer to 0 indicates weaker reliability. Based on the recommendation of Tavakol and Dennick (2011), a minimum Alpha score of 0.7 is required as acceptable reliability of the dataset. Reliability analysis of the dataset using SPSS generated a Cronbach's Alpha of 0.873, indicating a strong internal consistency within the dataset. Several statistical analyses were conducted to ascertain the suitability of the dataset and sample for factor analysis. Before this analysis, the dataset was assessed for normality to determine whether parametric or non-parametric statistical methods are suitable for the data analysis. The Wilk-Shapiro test was conducted based on the recommendations of Chou et al. (1998). The Wilk-

Shapiro test generated P-values less than 0.05 for all factors (Table 3), indicating that the data is non-normally distributed and instructs the use of non-parametric statistical methods to assess the suitability of the data set for factor analysis.

Based on this outcome, an ordinal-based non-parametric technique called the Mann-Whitney U-Test test was conducted to determine whether there are significant variations in the responses of the experts in academia and industry. The Mann-Whitney U-Test was implemented due to the three reasons: (a) the dependent variables (CRFs) were measured at the ordinal level using the Likert scale; (b) the independent variable consisted of two categorical, independent groups – experts from academia and industry; and (c) the data was not normally distributed (Norusis 2008). The asymptotic significance (2-tailed) p-values greater than 0.05 for all the factors (Table 3) indicated that there are no significant variations in the responses of the different experts, suggesting that the responses can be treated holistically (Ameyaw and Chan 2015). According to Lingard and Rowlinson (2006), a factor to sample size ratio of 1:5 is a prerequisite for exploratory factor analysis (hereafter, factor analysis). The dataset did not meet this condition since the ratio is 1: 2 (29/56) in the dataset. However, there are other overriding statistical analyses which can be conducted. First, the Kaiser-Meyer-Olkin (KMO) test statistic was used to measure the adequacy of the sample for factor analysis. A KMO test statistic of 0.647 was above the minimum threshold of 0.6 (Norusis 2008), indicating that the sample is adequate for factor analysis. Second, Bartlett's test of sphericity was carried out to determine whether the correlation matrix is significantly different from an identity matrix. A Pearson Chi-square, $\chi^2 = 1076.806$, and $p < 0.000$, indicated that the correlation matrix is not an identity matrix. Considering the Cronbach's Alpha value of 0.873, the KMO test statistic and Bartlett's test of sphericity, the dataset was deemed suitable for factor analysis.

According to Fang et al. (2004), factor analysis is a multivariate statistical method used to measure variability among observed, correlated variables, and the possibility of categorizing related factors. Due to the unique power of factor reduction and clustering (Brown 2015), factor analysis is widely used in the CEM research domain to reduce, cluster and manage a large set of risk factors. Thus, factor analysis was used to evaluate and cluster the risk factors in the implementation of MiC projects.

### *Fuzzy logic and fuzzy synthetic evaluation analysis*

Fuzzy logic is based on fuzzy set theory. Zadeh (1965) propounded fuzzy set theory to mathematically deal with objects which are imprecisely defined with grades of a continuum. Zadeh (1975) introduced linguistic variables to approximate reasoning using the fuzzy sets. Fuzzy set theory has the power to precisely and objectively explain and quantify ill-defined and imprecise information. Mathematically, a fuzzy set takes the form of membership functions which allocate grades of membership to define the extent of association of each element in the universe of discourse to the concept represented by a fuzzy set (Ameyaw and Chan 2015).

These membership grades are represented using real numbers that range between a closed interval of zero to one, where zero represents no membership, and one represents full membership in the fuzzy set. It employs linguistic variables and terms to model the characteristic vagueness in the human cognitive process.  For this reason, fuzzy logic has been used in a multi-attribute decision-making problem. Notably, the fuzzy synthetic evaluation (FSE) analysis is widely used in CEM research domain to quantitatively evaluate and model risk factors. For instance, Ameyaw and Chan (2015) used FSE to evaluate and rank risk factors in public-private partnership water projects; Wuni and Shen (2019) used FSE to allocate risk events in the supply chain of MiC; and Zafar et al. (2019) used FSE to analyze time overrun risk factors in highway projects. This study used FSE to evaluate and rank the risk factors in the implementation of MiC projects because the technique can be used to make a meaningful quantitative assessment of the fuzzy linguistic variables such as least critical, fairly critical, etc. as used in the current study. This research adopted the FSE protocol established in Ameyaw and Chan (2015), as shown in Figure 2. Details of each stage are discussed in the next section.

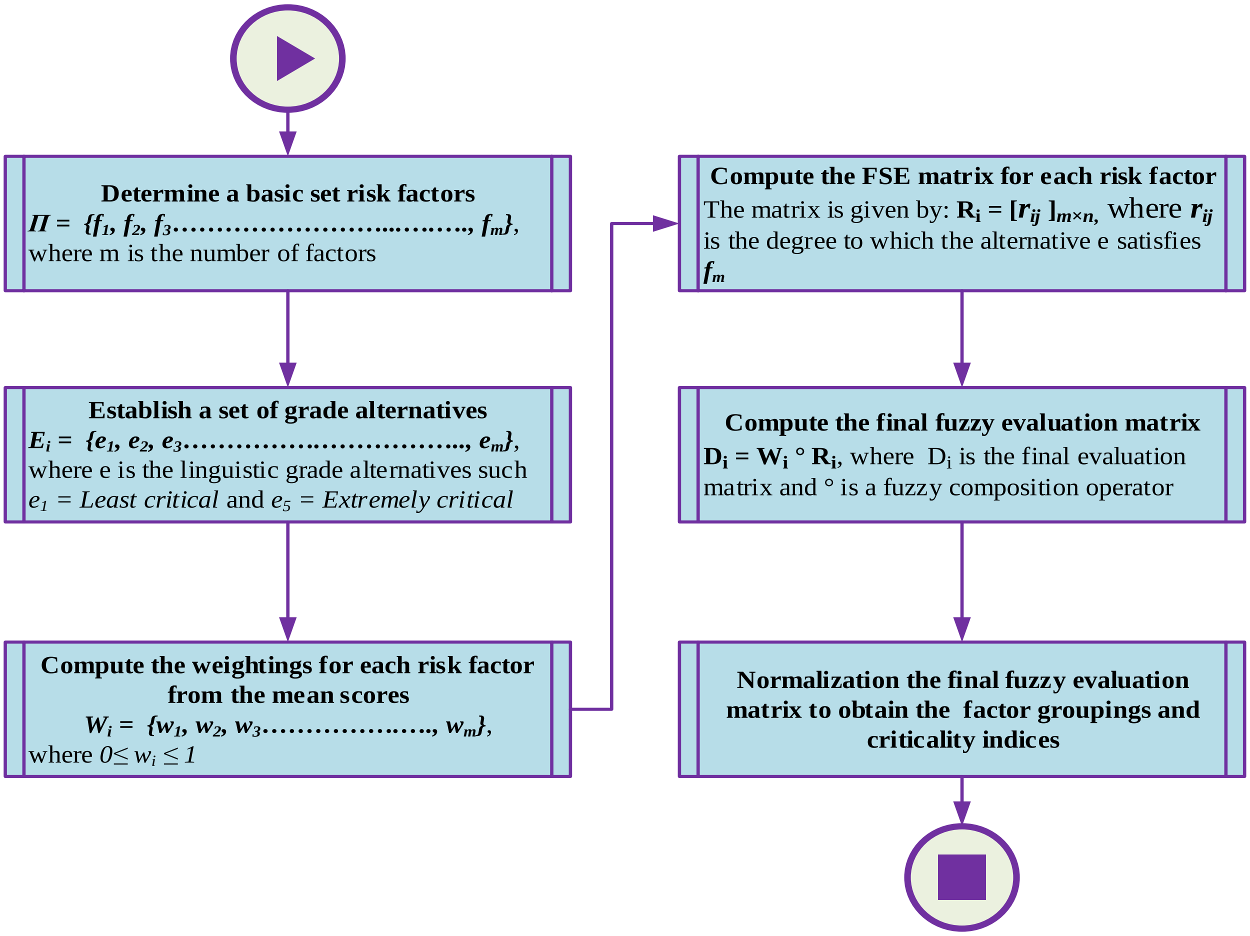

**Figure 2**. Flowchart of the fuzzy synthetic evaluation procedure

## Data analysis and results

### *Background information of the international experts*

One of the setbacks of international surveys is data quality problems. This could arise from the engagement of inappropriate or inexperienced respondents. Engaging respondents with substantial practical and theoretical knowledge of the subject matter can resolve this. Table 2 shows the work experience, job category, and the country in which the expert obtained their experiences. From Table 2, the majority of the experts were from academia but had substantial practical and research experience in MiC project implementation. These experts have strong links with industry and are regularly engaged in solving difficult challenges. About 51.8% of the respondents had at least 5 years' experience with MiC projects, and about 28.6% of them had over 11 years' experience and knowledge in MiC projects. Thus, the engaged experts had enough practical and research experience to comment on the risk factors in the application of MiC. These experts had worked in over 18 countries distributed across the six continents. Although the experts were asked to indicate the country in which they were engaged in the MiC projects, some indicated that they had extensive experience in the technology in more than 1 country.

**Table 2**. Background data of the international experts

| Attribute | Sub-attribute | Responses | % Responses |
|---|---|---|---|
| Years of MiC work experience | Below 5 years | 27 | 48.2 |
| | 5 - 10 years | 13 | 23.2 |
| | 11 - 15 years | 5 | 8.9 |
| | 16 - 20 years | 2 | 3.6 |
| | 21years and above | 9 | 16.1 |
| | ***Total*** | ***56*** | ***100.0*** |
| Country | United States | 10 | 17.9 |
| | Canada | 8 | 14.3 |
| | China | 7 | 12.5 |
| | Hong Kong | 7 | 12.5 |
| | Australia | 5 | 8.9 |
| | Malaysia | 4 | 7.1 |
| | United Kingdom | 4 | 7.2 |
| | Brazil | 1 | 1.8 |
| | Finland | 1 | 1.8 |
| | Germany | 1 | 1.8 |
| | Greece | 1 | 1.8 |
| | Lebanon | 1 | 1.8 |
| | Singapore | 1 | 1.8 |
| | Slovakia | 1 | 1.8 |
| | Spain | 1 | 1.8 |
| | Sweden | 1 | 1.8 |
| | Switzerland | 1 | 1.8 |
| | Tanzania | 1 | 1.8 |
| | ***Total*** | ***56*** | ***100.0*** |

The experts had worked in developing, transition and developed economies and thus, their holistic opinions constitute a useful knowledge base in the assessment of the risk factors. The geospatial distribution of experts is unique and comprehensive because it includes countries with the most advanced and successful MiC projects and thus, their collective opinions could be quite useful in most countries. Figure 3 shows the project types in which the experts had been engaged in. Majority of the experts (40) had worked on residential MiC projects because most countries are using the technology to respond to the growing housing crisis across the globe (Wuni and Shen 2019d, Wuni *et al.* 2019).

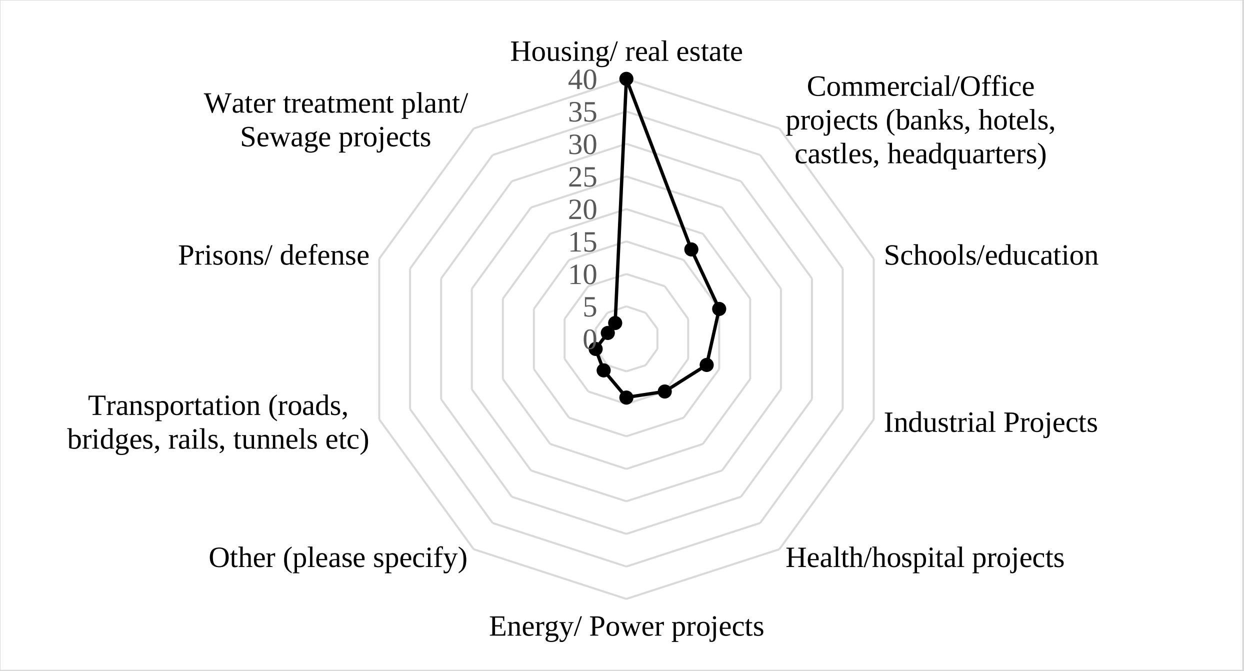

**Figure 3**. Types of MiC projects worked on by international experts.

Figure 3 also shows that the experts had worked on several MiC project types, and thus, their opinions on the risk factors draw on experience, research, and knowledge of different MiC projects. This further highlights the quality and representativeness of the experts in the study.

### *Identifying the critical risk factors of MiC projects*

The mean score analysis was used to identify the critical risk factors associated with the implementation of MiC projects. This statistic is widely and commonly used in CEM research domain to explore the average evaluation of risk factors on the Likert scale. Based on the grades of the 5-point Likert scale used in the study, a mean score of 3 or more indicates that the risk factor is at least critical (Osei-Kyei *et al.* 2017, Zafar *et al.* 2019) in MiC projects. Table 3 shows the results of the mean score indices of the risk factors. The mean score analysis (Table 3) results indicate that the experts assessed 23 of the 29 risk factors as critical in MiC projects. These risk factors deserve the critical attention of investors, contractors, and policymakers and thus, require further in-depth evaluation. This implies that the register of risk factors established in Wuni et al. (2019) was appropriate and useful. The top 5 critical risk factors (CRFs) include poor supply chain integration (3.80); higher initial capital cost (3.59); limited MiC expertise and experience (3.52); modular installation errors, complex rectifications and reworks (3.46); and stakeholder fragmentation and management complexity (3.39).

**Table 3**. Mean score ranking of the risk factors for MiC Projects

| **S.N.** | **Risks Factors** | **Mean** | **SD** | **Rank** | **Shapiro - Wilk Test** | **Mann-Whitney U-Test** |
|---|---|---|---|---|---|---|
| RF3 | Poor supply chain integration and disturbances | 3.80 | 0.90 | 1 | 0.000* | 0.627 |
| RF2 | Higher initial capital cost | 3.59 | 1.07 | 2 | 0.000* | 0.850 |
| RF10 | Limited MiC expertise and experience | 3.52 | 0.91 | 3 | 0.000* | 0.769 |
| RF17 | Modular installation errors, complex rectifications and reworks | 3.46 | 0.87 | 4 | 0.000* | 0.522 |
| RF1 | Stakeholder fragmentation and management complexity | 3.39 | 1.04 | 5 | 0.000* | 0.076 |
| RF7 | Defective design and change order | 3.38 | 1.15 | 6 | 0.000* | 0.538 |
| RF18 | Poor cooperation and communication among project participants | 3.38 | 0.96 | 6 | 0.000* | 0.735 |
| RF9 | Inefficient scheduling | 3.32 | 1.01 | 8 | 0.000* | 0.768 |
| RF20 | Unsupportive planning and building regulations | 3.30 | 1.06 | 9 | 0.000* | 0.215 |
| RF6 | Lack of MiC design codes and standards | 3.29 | 1.28 | 10 | 0.000* | 0.886 |
| RF21 | Limited capacity of modular manufacturers/suppliers | 3.29 | 1.07 | 10 | 0.001* | 0.950 |
| RF26 | Diseconomies of scale and longer break-even period | 3.27 | 1.07 | 12 | 0.000* | 0.486 |
| RF24 | Unable to freeze design early | 3.25 | 1.24 | 13 | 0.000* | 0.333 |
| RF8 | Supply chain information gap and inconsistency | 3.23 | 0.89 | 14 | 0.000* | 0.409 |
| RF29 | Geometric and dimensional intolerances | 3.18 | 1.01 | 15 | 0.001* | 0.875 |
| RF12 | Complex interfacing between systems | 3.16 | 1.06 | 16 | 0.000* | 0.764 |
| RF19 | Modular design complexity | 3.14 | 1.03 | 17 | 0.000* | 0.082 |
| RF4 | Delays in delivery of modules to site | 3.11 | 0.98 | 18 | 0.000* | 0.531 |
| RF11 | Shortage of modular components | 3.11 | 1.11 | 18 | 0.000* | 0.934 |
| RF27 | Modular production system failure | 3.09 | 4.10 | 20 | 0.000* | 0.586 |
| RF15 | Inexperience of contractors in MiC | 3.09 | 0.72 | 21 | 0.000* | 0.550 |
| RF16 | Specialist skilled labour requirement | 3.07 | 0.95 | 22 | 0.000* | 0.567 |
| RF25 | Higher prices of modules | 3.00 | 1.11 | 23 | 0.000* | 0.505 |
| RF23 | Absence of standardized modules | 2.95 | 1.07 | 24 | 0.001* | 0.709 |
| RF14 | Transportation restrictions | 2.93 | 0.99 | 25 | 0.000* | 0.770 |
| RF28 | Lack of best management practices | 2.93 | 0.83 | 25 | 0.000* | 0.503 |
| RF22 | Manual handling of heavy modules | 2.79 | 1.17 | 27 | 0.000* | 0.733 |
| RF5 | Poor government support and regulations | 2.75 | 1.05 | 28 | 0.000* | 0.403 |
| RF13 | Weather disruptions and force majeure | 2.48 | 0.97 | 29 | 0.000* | 0.104 |

Note*: The Shapiro – Wilk test was significant at the 0.05 significance level, indicating the data were not normally distributed.

However, the 20th ranked critical risk factor (RF27) scored a standard deviation of 4.10. This is quite suspicious because it indicates that experts' ratings for the risk factor were widely dispersed around the statistical mean. The implication may be that the experts do not have consensus or unanimous opinion on the criticality of the risk factor. Perhaps, its relative importance varies considerably in different geospatial context or project type. However, it was considered due to the higher mean score, but future research should measure its significance in another context. RF1, F2, and RF3 were ranked among the top 5 critical risk factors (CRFs) in Wuni et al. (2019), suggesting that the number of times a risk factor is cited in studies might reflect its significance and criticality.

Six risk factors were evaluated below the critical threshold of 3.0 on the 5-point grading scale by the experts. These include absence of standardized modules (2.95); transportation restrictions (2.93); lack of best management practices (2.93); manual handling of heavy modules (2.79); poor government support and regulations (2.75); and weather disruptions and force majeure (2.48). The scores of the first 5 factors evaluated as not critical by the experts have scores closer to critical threshold of 3.0, suggesting that they could be critical in some countries and hence, need to be considered in MiC risk planning and management. Again, even though RF13 recorded the lowest mean score and has been assessed as least critical, this factor, in reality, constitute a CRF in some countries. For instance, in Hong Kong, the strong wind forces from typhoons present a significant compromise and challenge to the structural stability and integrity of high-rise MiC projects (Pan and Hon 2018, Wuni *et al.* 2019). Indeed, these weather elements could significantly affect schedule by sending workers off the job-site for days; which is extremely significant in the case of six-day cycle assembly (Li, Xu, *et al.* 2018).

### ***Factor analysis of the critical risk factors in the implementation of MiC projects***

A principal component analysis of the 23 CRFs using Varimax Rotation converged in 8 iterations and generated a 4-factor solution with eigenvalues greater than 1, explaining 72.616% of the total variance. Considering that there is no existing study which classified the various risk factors examined in the current study, the characteristics and nature of the individual risk factors under each factor grouping (hereafter principal risk factors, PRFs) were used to determine a nomenclature for each PRF. The 23 CRFs were classified into 4 PRFs comprising stakeholder and supply chain risks, PRF1 (with 9 CRFs); design and capabilities risks, PRF2 (with 9 CRFs); financing risks, PRF3 (with 3 CRFs); and regulatory risks, PRF4 (with 2 CRFs). There are some overlaps within the risk factors in the various PRFs. However, no attempt was made to move the risk factors to other PRF because of the need for objectivity in the evaluation process. According to Ameyaw and Chan (2015), classification of the risk factors into factor groupings offer two advantages: (i) the PRFs are used as input variables in the assessment of the overall risk level of MiC projects and (ii) the PRFs offers a systematic framework and basis for effective risk management by reducing the need to deal directly with a long risk factor register. The risk factors and PRFs in Table 4 form the basis for the fuzzy synthetic evaluation analysis of the risk factors in the implementation of MiC projects.

**Table 4**. Critical risk factor extraction and loadings

| Critical risk factors (CRFs) /Principal risk factors (PRFs) | Factor loadings | Eigen-value | % of variance explained | Cumulative % of variance explained |
|---|---|---|---|---|
| *Stakeholder and supply chain risks (PRF1)* | | *11.257* | *40.205* | *40.205* |
| Stakeholder fragmentation and management complexity | 0.953 | | | |
| Delays in delivery of modules to site | 0.827 | | | |
| Complex interfacing between systems | 0.825 | | | |
| Supply chain information gap and inconsistency | 0.814 | | | |
| Shortage of modular components | 0.755 | | | |
| Poor supply chain integration and disturbances | 0.674 | | | |
| Modular production system failure | 0.670 | | | |
| Inefficient scheduling | 0.485 | | | |
| Poor cooperation and communication among project participants | 0.451 | | | |
| *Design and capabilities risks (PRF2)* | | *5.411* | *19.326* | *59.531* |
| Geometric and dimensional intolerances | 0.852 | | | |
| Unable to freeze design early | 0.772 | | | |
| Modular installation errors, complex rectifications and reworks | 0.713 | | | |
| Inexperience of contractors in MiC | 0.676 | | | |
| Specialist skilled labour requirement | 0.607 | | | |
| Limited capacity of modular manufacturers/suppliers | 0.529 | | | |
| Limited MiC expertise and experience | 0.554 | | | |
| Modular design complexity | 0.542 | | | |
| Defective design and change order | 0.509 | | | |
| *Financing risks (PRF3)* | | *2.088* | *7.458* | *66.989* |
| Higher prices of modules | 0.734 | | | |
| Diseconomies of scale and longer break-even period | 0.661 | | | |
| Higher initial capital cost | 0.566 | | | |
| *Regulatory risks (PRF4)* | | *1.576* | *5.627* | *72.616* |

| | |
|---|---|
| Lack of MiC design codes and standards | 0.768 |
| Unsupportive planning and building regulations | 0.754 |

***Fuzzy synthetic evaluation of the CRFs in the implementation of MiC projects***

Drawing on the outcome of the factor analysis, three levels of FSE of risk of MiC projects are derived. The third level involves evaluation of the criticality of risk factors within each PRF and the second level involves assessment of the criticality of the PRFs. The overall risk index (1st level) for MiC projects is then computed based on the criticality assessment of the individual PRFs. This is considered as a multi-factor and multi-level FSE (Ameyaw and Chan 2015) of the risk of MiC projects. The systematic implementation of the multi-level FSE is shown in Figure 2.

*Computing the weighting function of each CRF and PRF*: According to Lo (1999), the overall accuracy of the FSE model depends on the accuracy of the weightings assigned to each CRF and PRF. Various techniques are available for accurate computations of the weightings from survey data using a Likert scale such as the analytic hierarchy process, direct point allocation, unit weighting, tabulated judgment method, and normalized mean method (Hsiao 1998, Lo 1999, Ameyaw and Chan 2015). Based on the recommendation of Ameyaw and Chan (2015), the normalized mean method is used to compute the weightings of each CRF and PRF. Following the works of Xu et al. (2010), the weighting functions were derived through normalization of the mean scores of each CRF and PRF as:

$$w_i = \frac{M_i}{\sum_{i=1}^{5} M_i},\ 0 < w_i < 1, \text{ and } \sum_{i=1}^{n} w_i = 1 \qquad (1)$$

where $w_i$ is the weighting function of a specific CRF/PRF; $M_i$ is the mean score of each CRF/PRF; and $i$ ranges from 1 to 5 based on the 5-point grading scale. As shown in Figure 2, the weighting function is given by:

$$\mathrm{W}_i = \{w_1, w_2, \ldots\ldots\ldots\ldots, w_n\} \qquad (2)$$

For example, in Table 5, the mean score for RF3 is 3.80, and the total mean score for PRF1 is 29.59. The weighting for RF3 is computed using equation (1) as:

$$w_{RF3} = \frac{3.80}{3.80+3.39+3.38+3.32+3.23+3.16+3.11+3.11+3.09} = \frac{3.80}{29.59} = 0.128$$

Similarly, the weighting functions of the remaining risk factors under PRF1 – PRF4 are computed using the same procedure (Table 5), and the normalized weighting function sets satisfy the condition in Equation (1) for each PRF (Table 5). For example, the normalized weighting function for PRF1 is given as:

$$\sum_{i=1}^{9} W_i = 0.128 + 0.115 + 0.114 + 0.112 + 0.109 + 0.107 + 0.105 + 0.105 + 0.104 = 1.000$$

**Table 5**. Weightings for the CRFs and PRFs for MiC projects

| S.N. | Factors | Mean for CRFs | Weightings for each CRF | Total Mean for each PRF | Weightings for each PRF |
|---|---|---|---|---|---|
| *PRF1* | *Stakeholder and supply chain risks* | | | *29.59* | *0.392* |
| RF3 | Poor supply chain integration and disturbances | 3.80 | 0.128 | | |
| RF1 | Stakeholder fragmentation and management complexity | 3.39 | 0.115 | | |
| RF18 | Poor cooperation and communication among project participants | 3.38 | 0.114 | | |
| RF9 | Inefficient scheduling | 3.32 | 0.112 | | |
| RF8 | Supply chain information gap and inconsistency | 3.23 | 0.109 | | |
| RF12 | Complex interfacing between systems | 3.16 | 0.107 | | |
| RF4 | Delays in delivery of modules to site | 3.11 | 0.105 | | |
| RF11 | Shortage of modular components | 3.11 | 0.105 | | |
| RF27 | Modular production system failure | 3.09 | 0.104 | | |
| *PRF2* | *Design and capabilities risks* | | *1.000* | *29.38* | *0.390* |
| RF10 | Limited MiC expertise and experience | 3.52 | 0.120 | | |
| RF17 | Modular installation errors, complex rectifications and reworks | 3.46 | 0.118 | | |
| RF7 | Defective design and change order | 3.38 | 0.115 | | |
| RF21 | Limited capacity of modular manufacturers/suppliers | 3.29 | 0.112 | | |
| RF24 | Unable to freeze design early | 3.25 | 0.111 | | |
| RF29 | Geometric and dimensional intolerances | 3.18 | 0.108 | | |
| RF19 | Modular design complexity | 3.14 | 0.107 | | |
| RF15 | Inexperience of contractors in MiC | 3.09 | 0.105 | | |
| RF16 | Specialist skilled labour requirement | 3.07 | 0.104 | | |
| *PRF3* | *Financing risks* | | *1.000* | *9.86* | *0.131* |
| RF2 | Higher initial capital cost | 3.59 | 0.364 | | |
| RF26 | Diseconomies of scale and longer break-even period | 3.27 | 0.332 | | |
| RF25 | Higher prices of modules | 3.00 | 0.304 | | |
| *PRF4* | *Regulatory risks* | | *1.00* | *6.59* | *0.087* |
| RF20 | Unsupportive planning and building regulations | 3.30 | 0.501 | | |
| RF6 | Lack of MiC design codes and standards | 3.29 | 0.499 | | |

| | |
|---|---|
| Total PRF | 75.42 |

Considering the total mean scores of the PRFs (PRF1 = 29.59, PRF2 = 29.38, PRF3 = 9.86 and PRF4 = 6.59) as 75.42, the mean scores of each PRF can be normalized to obtain their weighting functions using equation (1) as:

$$W_{\mathrm{PRF1}} = \frac{29.59}{29.59+29.38+9.86+6.59} = \frac{29.59}{75.42} = 0.392$$

$$W_{\mathrm{PRF2}} = \frac{29.38}{29.59+29.38+9.86+6.59} = \frac{29.38}{75.42} = 0.390$$

$$W_{\mathrm{PRF3}} = \frac{9.86}{29.59+29.38+9.86+6.59} = \frac{9.86}{75.42} = 0.131$$

$$W_{\mathrm{PRF4}} = \frac{6.59}{29.59+29.38+9.86+6.59} = \frac{6.59}{75.42} = 0.087$$

Similarly, the sum of normalized weightings of the all the PRFs equals 1. The weightings for the individual risk factors and PRFs form the basis for calibrating the membership functions in the next section.

*Computing the membership functions of each CRF and PRF*: The membership function (MF) of each CRF is computed from the percentage responses of the experts. The membership function of each PRF is further computed from the membership functions of the CRFs within each factor grouping. The membership functions of each CRF and PRF is then used to develop the fuzzy matrix (Figure 3). To compute the MF for each CRF, the analyst needs to ascertain the percentage responses of the experts for the various grading point scales comprising *least critical* (LC), *fairly critical* (FC), *critical* (C), *very critical* (VC), and *extremely critical* (EC). For example, the data analysis shows that 1.8% of the experts assessed “stakeholder fragmentation and management complexity (CRF1)” as *least critical*, 16.1% assessed it as *fairly critical*, 42.9% assessed it as *critical*, 19.6% assessed as *very critical* and 19.6% also assessed it as *extremely critical*. Thus, the membership function for CRF1 is computed as:

$$\mathrm{MF}_{\mathrm{CRF1}} = \frac{0.018}{\mathrm{LC}\ (1)} + \frac{0.161}{\mathrm{FC}\ (2)} + \frac{0.429}{\mathrm{C}\ (3)} + \frac{0.196}{\mathrm{LC}\ (4)} + \frac{0.196}{\mathrm{VC}\ (5)} \quad (3)$$

Thus, the membership function of CRF1 can be expressed otherwise as (0.02, 0.16, 0.43, 0.20, 0.20). The membership functions of the rest of the CRFs are computed using the same approach as shown in Table 6. The membership functions (Level 3) of the individual CRFs form the basis for computing the membership functions (Level 2) of the PRF. However, the computations of the membership functions of the PRFs require the fuzzy evaluation matrix. Based on the works of Ameyaw and Chan (2015), the fuzzy evaluation matrix is given by:

**Table 6.** Membership functions (MF) for all CRFs and PRFs for MiC projects

| S.N. | CRFs and PRF | Weightings | Membership functions for each CRF (Level 3) | Membership Function for each PRF (Level 2) |
|---|---|---|---|---|
| *PRF1* | *Stakeholder and supply chain risks* | | | *(0.03, 0.18, 0.36, 0.30, 0.12)* |
| RF3 | Poor supply chain integration and disturbances | 0.128 | (0.00, 0.09, 0.25, 0.43, 0.23) | |
| RF1 | Stakeholder fragmentation and management complexity | 0.115 | (0.02, 0.16, 0.43, 0.20, 0.20) | |
| RF18 | Poor cooperation and communication among project participants | 0.114 | (0.02, 0.20, 0.27, 0.43, 0.09) | |
| RF9 | Inefficient scheduling | 0.112 | (0.05, 0.11, 0.43, 0.27, 0.13) | |
| RF8 | Supply chain information gap and inconsistency | 0.109 | (0.02, 0.16, 0.48, 0.25, 0.09) | |
| RF12 | Complex interfacing between systems | 0.107 | (0.04, 0.27, 0.30, 0.29, 0.11) | |
| RF4 | Delays in delivery of modules to site | 0.105 | (0.04, 0.27, 0.30, 0.34, 0.05) | |
| RF11 | Shortage of modular components | 0.105 | (0.11, 0.14, 0.38, 0.29, 0.09) | |
| RF27 | Modular production system failure | 0.104 | (0.00, 0.27, 0.46, 0.18, 0.09) | |
| *PRF2* | *Design and capabilities risks* | | | *(0.05, 0.17, 0.35, 0.33, 0.11)* |
| RF10 | Limited MiC expertise and experience | 0.120 | (0.02, 0.14, 0.23, 0.52, 0.09) | |
| RF17 | Modular installation errors, complex rectifications and reworks | 0.118 | (0.02, 0.09, 0.41, 0.38, 0.11) | |
| RF7 | Defective design and change order | 0.115 | (0.07, 0.18, 0.20, 0.41, 0.14) | |
| RF21 | Limited capacity of modular manufacturers/suppliers | 0.112 | (0.04, 0.21, 0.32, 0.29, 0.14) | |
| RF24 | Unable to freeze design early | 0.111 | (0.09, 0.23, 0.18, 0.34, 0.16) | |
| RF29 | Geometric and dimensional intolerances | 0.108 | (0.05, 0.18, 0.39, 0.29, 0.09) | |
| RF19 | Modular design complexity | 0.107 | (0.05, 0.18, 0.46, 0.18, 0.13) | |
| RF15 | Inexperience of contractors in MiC | 0.105 | (0.00, 0.18, 0.59, 0.20, 0.04) | |
| RF16 | Specialist skilled labour requirement | 0.104 | (0.07, 0.16, 0.43, 0.30, 0.04) | |
| *PRF3* | *Financing risks* | | | *(0.05, 0.23, 0.22, 0.38, 0.13)* |
| RF2 | Higher initial capital cost | 0.364 | (0.02, 0.20, 0.16, 0.43, 0.20) | |
| RF26 | Diseconomies of scale and longer break-even period | 0.332 | (0.02, 0.29, 0.23, 0.34, 0.13) | |
| RF25 | Higher prices of modules | 0.304 | (0.13, 0.20, 0.27, 0.38, 0.04) | |
| *PRF4* | *Regulatory risks* | | | *(0.09, 0.16, 0.26, 0.35, 0.14)* |
| RF20 | Unsupportive planning and building regulations | 0.501 | (0.05, 0.18, 0.29, 0.38, 0.11) | |
| RF6 | Lack of MiC design codes and standards | 0.499 | (0.13, 0.14, 0.23, 0.32, 0.18) | |

$$R_i = \begin{bmatrix} \mathrm{MF}_{u1} \\ \mathrm{MF}_{u2} \\ \mathrm{MF}_{u3} \\ \dots\dots. \\ \mathrm{MF}_{un} \end{bmatrix} = \begin{bmatrix} C_{1_{u_{i1}}} & C_{2_{u_{i1}}} & C_{3_{u_{i1}}} & C_{4_{u_{i1}}} & C_{5_{u_{i1}}} \\ C_{1_{u_{i2}}} & C_{2_{u_{i2}}} & C_{3_{u_{i1}}} & C_{4_{u_{i2}}} & C_{5_{u_{i2}}} \\ C_{1_{u_{i3}}} & C_{2_{u_{i3}}} & C_{3_{u_{i3}}} & C_{4_{u_{i3}}} & C_{5_{u_{i3}}} \\ \dots. & \dots. & \dots. & \dots. & \dots. \\ C_{1_{u_{in}}} & C_{2_{u_{in}}} & C_{3_{u_{in}}} & C_{4_{u_{in}}} & C_{5_{u_{in}}} \end{bmatrix} \tag{4}$$

Where $R_i$ denotes the fuzzy membership functions for the CRFs within a given PRF (called fuzzy matrix) and $MF_{u1}$ to $MF_{un}$ denotes the membership functions of n CRFs in a given PRF. The values for $C_1$ to $C_5$ in equation (4) are the Level 3 membership functions shown in Table 6. Given the fuzzy matrix ($R_i$) and the weightings ($W_i$), the fuzzy evaluation matrix ($D_i$), as shown in Figure 2 can be computed using the equation:

$$D_i = W_i \bullet R_i = \{w_1, w_2, w_{3,..,} w_n\} * \begin{vmatrix} C_{1_{u_{i1}}} & C_{2_{u_{i1}}} & C_{3_{u_{i1}}} & C_{4_{u_{i1}}} & C_{5_{u_{i1}}} \\ C_{1_{u_{i2}}} & C_{2_{u_{i2}}} & C_{3_{u_{i1}}} & C_{4_{u_{i2}}} & C_{5_{u_{i2}}} \\ C_{1_{u_{i3}}} & C_{2_{u_{i3}}} & C_{3_{u_{i3}}} & C_{4_{u_{i3}}} & C_{5_{u_{i3}}} \\ \dots. & \dots. & \dots. & \dots. & \dots. \\ C_{1_{u_{in}}} & C_{2_{u_{in}}} & C_{3_{u_{in}}} & C_{4_{u_{in}}} & C_{5_{u_{in}}} \end{vmatrix} = (d_{i1}, d_{i2}, \dots, d_{in}) \tag{5}$$

where; $d_{in}$ denotes the degree of membership of the grade alternative for a given PRF and "●" denotes a fuzzy composite operator. For example, PRF3 contains three CRFs comprising RF2, RF25, and RF26. The weights of the CRFs include RF2 (0.364), RF25 (0.304), and RF26 (0.332) as shown in Table 6 and thus, the weighting function for PRF3 is given by:

$$W_{PRF3} = \{0.364, 0.304, 0.332\}$$

Considering the membership functions of RF2, RF25, and RF26 (Table 6), the fuzzy evaluation matrix for PRF3 is given by:

$$R_{PRF3} = \begin{vmatrix} MF_{RF2} \\ MF_{RF25} \\ MF_{RF26} \end{vmatrix} = \begin{vmatrix} 0.02 & 0.20 & 0.16 & 0.43 & 0.20 \\ 0.13 & 0.20 & 0.27 & 0.38 & 0.04 \\ 0.02 & 0.29 & 0.23 & 0.34 & 0.13 \end{vmatrix}$$

Thus, using equation (5), the fuzzy evaluation matrix for PRF3 is computed as follows:

$$D_{PRF3} = W_{PRF3} \bullet R_{PRF3} = (0.364, 0.304, 0.332) * \begin{vmatrix} 0.02 & 0.20 & 0.16 & 0.43 & 0.20 \\ 0.13 & 0.20 & 0.27 & 0.38 & 0.04 \\ 0.02 & 0.29 & 0.23 & 0.34 & 0.13 \end{vmatrix}$$

= (0.05, 0.23, 0.22, 0.38, 0.13)

Similarly, the fuzzy evaluation matrix of PRF1, PRF2 and PRF4 are obtained using the weighting functions set in column 3 and the membership functions of the CRFs in column 4 under each PRF, as shown in Table 6.

*Computing the criticality indices of the PRFs and the overall risk index*: The criticality indices of the PRFs can be computed as a product of the fuzzy evaluation matrix of each PRF and the grade alternatives on the Likert scale adopted for the study. Mathematically, the criticality index of each PRF is given by:

$$\mathrm{PRF_{Index}} = \sum_{i=1}^{5}(\mathrm{D}_i \times \mathrm{E}_i) \tag{6}$$

Where; $D_i$ denotes the fuzzy evaluation matrix of a given PRF and $E_i$ denotes the grade alternatives of the adopted 5-point Likert scale (Figure 2). Using equation (6), the criticality indices of the PRF are computed as follows:

PRF1 = (0.03, 0.18, 0.36, 0.30, 0.12) × (1, 2, 3, 4, 5) = (0.03*1 + 0.18*2 + 0.36*3 + 0.30*4 + 0.12*5) = **3.31**

PRF2 = (0.05, 0.17, 0.35, 0.33, 0.11) × (1, 2, 3, 4, 5) = (0.05*1 + 0.17*2 + 0.35*3 + 0.33*4 + 0.11*5) = **3.28**

PRF3 = (0.05, 0.23, 0.22, 0.38, 0.13) × (1, 2, 3, 4, 5) = (0.05*1 + 0.23*2 + 0.22*3 + 0.38*4 + 0.13*5) = **3.34**

PRF4 = (0.09, 0.16, 0.26, 0.35, 0.14) × (1, 2, 3, 4, 5) = (0.09*1 + 0.16*2 + 0.26*3 + 0.35*4 + 0.14*5) = **3.32**

The above criticality indices are considered the second level fussy synthetic evaluation analysis. The final evaluation matrix of overall risk level index for MiC projects can be computed using the fuzzy evaluation matrices of the PRFs and their associated total weightings. The weightings for PRF1, PRF2, PRF3, and PRF4 are 0.392, 0.390, 0.131, and 0.087, respectively, as shown in Table 5. The fuzzy evaluation matrices of the PRFs are PRF1 (0.03, 0.18, 0.36, 0.30, 0.12), PRF2 (0.05, 0.17, 0.35, 0.33, 0.11), PRF3 (0.05, 0.23, 0.22, 0.38, 0.13), and PRF4 (0.09, 0.16, 0.26, 0.35, 0.14), as shown in Table 6. Therefore, the following functions can be deduced.

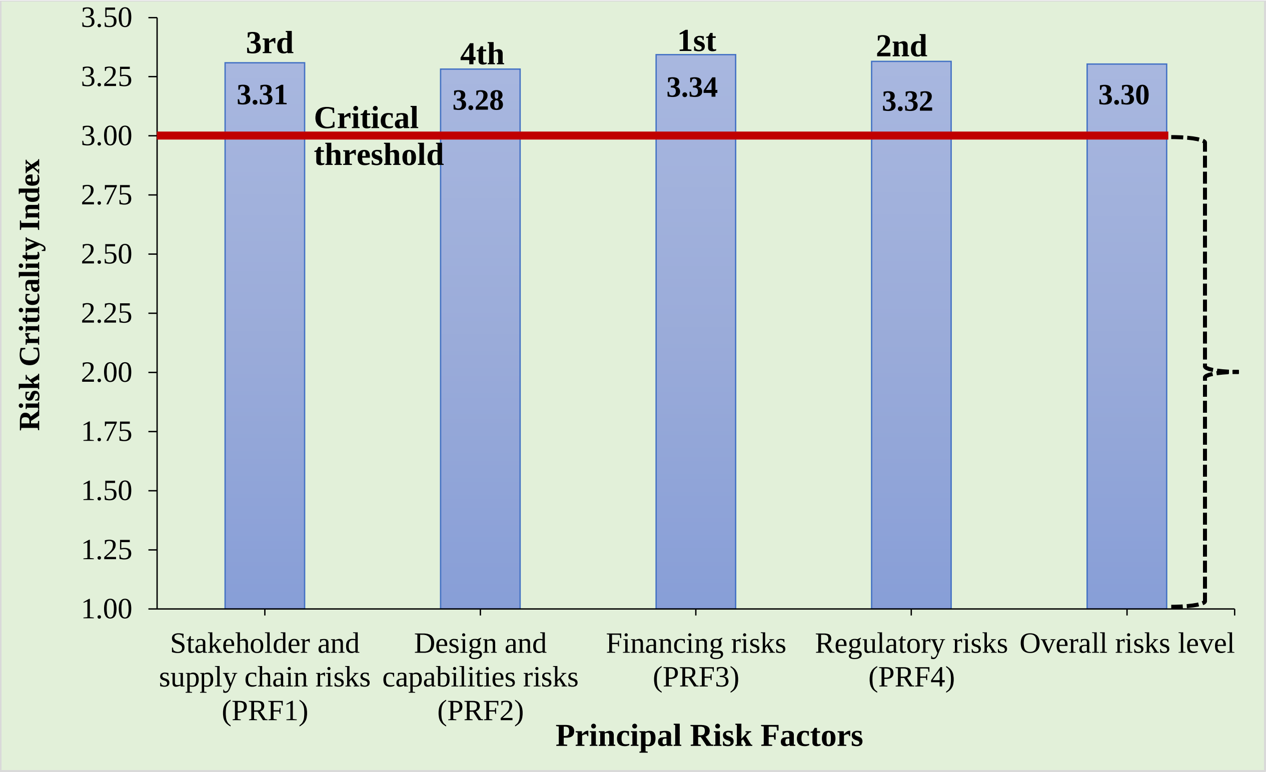

**Figure 4**. Criticality indices of the PRFs and overall risk level of MiC projects

$W_{Overall} = (0.392, 0.390, 0.131, 0.087)$

$$R_{Overall} = \begin{vmatrix} MF_{PRF1} \\ MF_{PRF2} \\ MF_{PRF3} \\ MF_{PRF4} \end{vmatrix} = \begin{vmatrix} 0.03 & 0.18 & 0.36 & 0.30 & 0.12 \\ 0.05 & 0.17 & 0.35 & 0.33 & 0.11 \\ 0.05 & 0.23 & 0.22 & 0.38 & 0.13 \\ 0.09 & 0.16 & 0.26 & 0.35 & 0.14 \end{vmatrix}$$

Thus, the final fuzzy evaluation matrix ($D_{Overall}$) of the overall risk level for MiC projects can be computed using equation (5) as follows:

$$D_{Overall} = W_{Overall} \bullet R_{Overall} = (0.392, 0.390, 0.131, 0.087) \times \begin{vmatrix} 0.03 & 0.18 & 0.36 & 0.30 & 0.12 \\ 0.05 & 0.17 & 0.35 & 0.33 & 0.11 \\ 0.05 & 0.23 & 0.22 & 0.38 & 0.13 \\ 0.09 & 0.16 & 0.26 & 0.35 & 0.14 \end{vmatrix}$$

$$= (0.05, 0.18, 0.33, 0.33, 0.12)$$

The overall risk index (Level 1) for MiC projects is computed as a product of the final fuzzy evaluation matrix ($D_{Overall}$) and the grade alternatives (1, 2, 3, 4, 5) on the Likert scale adopted for the study. Mathematically, the overall risk level index for MiC Projects is calculated using equation (6) as follows:

**Overall risk level index** = (0.05, 0.18, 0.33, 0.33, 0.12) × (1, 2, 3, 4, 5)

= (0.05*1 + 0.18*2 + 0.33*3 + 0.33*4 + 0.12*5) = 3.30 **(Critical)**

*Developing a risk assessment model for MiC projects*: Given the indices for the four PRFs, it is useful to develop a model which can facilitate risk assessment in MiC projects. Drawing on the works of Chen et al. (2019), a linear additive approach is used to develop the risk assessment model because it is simple, easy to understand, and can be supported by the criticality indices of the various PRFs. To develop the overall MiC risk assessment model, the criticality indices of the four PRFs are normalized using equation (1) to obtain their criticality weightings. From the computations above, the criticality indices of PRF1, PRF2, PRF3, and PRF4 are 3.31, 3.28, 3.34, and 3.32, respectively. Thus, the normalized criticality weighting for PRF1 is given by:

$$\mathrm{W}_{\mathrm{PRF1}} = \frac{3.31}{3.31+3.28+3.34+3.32} = \frac{3.31}{13.25} = 0.250$$

Similarly, the normalized criticality weightings for PRF2, PRF3, and PRF4 are computed as 0.246, 0.252, and 0.251, respectively. Therefore, the linear additive risk assessment index (RAI) for MiC projects is given by:

$\mathbf{RAI}_{\textbf{(MiC projects)}}$ = **0.250***(stakeholder and supply chain risks) + **0.246***(design and capabilities risks) + **0.252***(financing risks) + **0.251***(regulatory risks)

## Discussions and implications of the results

The statistics in Figure 4 shows the criticality indices of principal risk factors and the overall risk level index of MiC projects. The PRFs are also ranked according to their criticality indices. The FSE analysis resulted in an overall risk index of 3.30, indicating that MiC projects in both developing and developed countries have some significant risks (Wuni and Shen 2019c, Wuni *et al.* 2019). Analysis of the summary results in Figure 4 shows that the indices of all the PRFs exceed the criticality threshold of 3.0 based on the 5-point Likert scale. This means all the risk factor groupings are at least critical and thus, policymakers, investors, and industry practitioners should examine, plan, and manage these risk factors in the implementation of MiC projects. The various PRFs are discussed in the following subsections.

***PRF1 - Stakeholder and supply chain risks***

This PRF explains about 40.21% of the variations in the risk profile of MiC projects and scored an Eigenvalue of 11.26 (Table 4). It comprises nine significant risk factors with a total mean of 29.59 and normalized weighting of 0.392 (Table 5). It has an overall risk level of 3.31 (Figure 4) and ranked 3rd among the four PRFs. Considering the nature of the nine CRFs under this PRF, the term "stakeholder and supply chain risks" holistically and appropriately describes the risks factors because they are associated with stakeholders and the MiC supply chain (Wuni and Shen 2019c). The nine CRFs of PRF1 were expected because they have been assessed as critical in previous studies. For instance, based on a systematic review, Wuni et al. (2019) found that stakeholder fragmentation and management complexity (RF1), poor supply chain integration and disturbances (RF3), delays in delivery of modules to site (RF4), supply chain information gap and inconsistency (RF8), and inefficient scheduling (RF9) ranked globally among the top 10 most CRFs in the application of MiC. Notably, there are several multidisciplinary stakeholders in the MiC supply chain with their unique goals and value systems (Luo *et al.* 2019). Yet, these stakeholders are fragmented along with the various segments of the MiC supply chain (Li *et al.* 2013, Wuni *et al.* 2019). This increases the complexity of stakeholder management in MiC projects and hence, could compromise the success of a project since all key stakeholders need to be coordinated to ensure smooth delivery of the MiC project.

Furthermore, the MiC supply chain comprises linked segments (Li *et al.* 2016) and thus, poor integration and resulting disturbances could trigger detrimental impact on the entire supply chain (Wuni *et al.* 2019). For instance, delay in the delivery of modular components to site resulted in significant schedule delays of MiC projects in Hong Kong (Li, Xu, *et al.* 2018). Luo et al. (2019) reported that poor cooperation and communication among project participants (RF18) constitute a significant risk factor because it could compromise the success of the MiC project from the very early stages. For instance, the poor cooperation could result in late design freeze which has a significant impact on the schedule of MiC projects. Wuni and Shen (2019a) found that modular production system failure (RF27) could trigger shortage in the supply of modules which translates into a shortage of modular components (RF11) on site, in cases where there is no safety stock. This implies that government and industry practitioners should understand and recognize the impact of these stakeholder and supply chain risk factors prior to and during the implementation of MiC projects.

***PRF2 - Design and capabilities risks***

This PRF explains about 19.33% of the variations in risk profile of MiC projects and scored an Eigenvalue of 5.411 (Table 4). It comprises nine significant risk factors with a total mean of 29.38 and normalized weighting of 0.390 (Table 5). It has an overall risk level of 3.28 (Figure 4) and ranked 4th among the four PRFs. Based on the nine CRFs under this PRF, the term "design and capabilities risks" best describe their nature and characteristics (Wuni and Shen 2019c). PRF2 describes the risk factors associated with the design stage and the capabilities (skills) required to deliver MiC projects. Luo et al. (2015) identified limited MiC expertise and experience (RF10) and inexperience of contractors in the MiC technology (RF15) as two CRFs in the implementation of MiC projects in China. Indeed, the unique engineering and installation requirements of MiC is challenging the traditional knowledge and expertise of contractors (Hwang *et al.* 2018a). The implementation of MiC requires some technical manufacturing skills and knowledge to ensure effective management of the projects. However, as MiC is still fledgling in many countries, contractors are yet to upgrade their skills set to meet the skills requirements of MiC projects, and thus their limited knowledge and inexperience amount to significant risk in the implementation of MiC projects (Wuni *et al.* 2019). Geometric and dimensional variability (RF29) constitute a CRF in MiC projects because intolerances beyond the allowable parameters could trigger expensive site-fit reworks (Shahtaheri *et al.* 2017, Enshassi *et al.* 2019).

Further, late design freeze (RF24) in MiC projects implies a delay in the manufacture of the components because the modules produced in the workshop are based on the final design (Wuni *et al.* 2019). This ultimately affects the schedule of MiC projects. In MiC, the modular components are the key driver of the project. Thus, limited capacity of modular manufacturers or suppliers (RF21) constitutes a recipe for the shortage of modular components on the jobsite. Where safety stock or Just-in-Time delivery arrangement is not made, failure to make a timely supply of the modules to the site will halt the entire installation process (Wuni *et al.* 2019). This will increase the cost of hired equipment and further trigger expensive schedule delay in the project (Li, Hong, *et al.* 2018). Wuni et al. (2019) ranked modular design complexity (RF19) and defective design and change order (RF7) among the top 10 CRFs in the application of MiC projects. Wang et al. (2018) found that the former (RF19) is a recipe for the latter (RF7). Deficiencies in the modular design trigger significant differences between modular production and assembly tolerances (Shahtaheri *et al.* 2017). Such defective design instructs significant alterations to the original design and scope of the MiC projects. However, there is almost zero tolerance for defective design and change order in MiC projects because the schedules of the workshop production become fixed, once initiated (Hsu *et al.* 2018). Changes in the scope of MiC projects are challenging to implement at later stages because there is little flexibility for these late design changes once the design is frozen. Finally, modular installation errors, complex rectifications and reworks (RF17) constitute a CRF because error rectification and reworks in MiC projects are prohibitively expensive to implement. In some cases, reworks require complete recycling and repetition of the entire MiC supply chain ranging from redesign to reinstallation. These engender significant risks to quality, cost, schedule, and overall client satisfaction (Wuni *et al.* 2019).

### *PRF3 - Financing risks*

This PRF explains about 7.46% of the variations in the risk profile of MiC projects and scored an Eigenvalue of 2.088 (Table 4). It comprises three significant risk factors with a total mean of 9.86 and normalized weighting of 0.131 (Table 5). However, it has an overall risk level of 3.34 (Figure 4) and ranked 1st among the four PRFs. The FSE analysis identified "financing risks" as the most critical PRF in the implementation of MiC projects. Although this was not expected because of the fewer number of CRFs under PRF3, it does indicate that the experts recognize the risk associated with financing MiC projects to be extremely profound. Under PRF3, higher initial capital cost (RF2) is considered the most CRF with a weighting of 0.364 (Table 6), followed by diseconomies of scale and longer break-even period (RF26) with a weighting of 0.332, and higher prices of modules (RF25) with a weighting of 0.304 (Table 6). Higher initial capital cost becomes even a more significant risk where there are no readily available modular manufacturers and suppliers. In this case, clients or developers will have to either import modules from other regions and incur expensive cross-border transportation costs (Pan and Hon 2018), or they may have to build new moulds, secure land for factory yards, build manufacturing plants, and warehouses for temporary storages of the produced modules. These require colossal sums of financing, which might not be justified in a market with uncertain demand for MiC projects (Hwang *et al.* 2018a).

Moreover, the lower demand for MiC projects may expose investors and developers to cost disadvantages due to diseconomies of scale. This risk is exacerbated because MiC projects take longer time to break even due to the higher initial capital cost. It is not surprising that the experts ranked PRF3 as the most critical risk factor grouping because industry practitioners are conservative and profit-oriented and will not implement technologies which are not tried and tested. Even in cases where modular manufacturers and suppliers are available, studies have shown that the prices of the modules tend to be high (Li *et al.* 2013, Luo *et al.* 2015, Li, Li, *et al.* 2017). The higher prices of the modules translate into a higher cost of construction.

### *PRF4 - Regulatory risks*

PRF4 constitutes the risk factors associated with general building regulations, MiC design codes, standards, and specification. The "regulatory risks" explains about 5.63% of the variations in the risk profile of MiC projects and scored an Eigenvalue of 1.576 (Table 4). It comprises two significant risk factors with a total mean of 6.59 and normalized weighting of 0.087 (Table 5). The two CRFs under PRF4 are “unsupportive planning and building regulations (RF20)” weighted 0.501 and “lack of MiC design codes and standards (RF6)” weighted 0.499. Although these factors are only two, their importance cannot be overemphasized because they are directly intertwined with major sections of the MiC project implementation process, ranging from statutory approval through to modular design and installation. For instance, if the design of a project lends itself to modularization and there are readily available project participants with the requisite skills set, the project might not even be initiated if the building regulations do not support MiC. Thus, any prior resources and time expended at the conceptual design stage and planning of the project might be wasted. This often occurs where local authorities and the government do not support the MiC technology (Mao *et al.* 2014, Luo *et al.* 2015). Thus, it becomes difficult to obtain a planning permit and statutory approval to proceed with the MiC project implementation process.

Furthermore, Wuni et al. (2019) ranked lack of MiC design codes and standards (RF20) among the top 10 CRFs in the application of MiC projects. Building regulations and design codes require that the design and construction of projects conform to some built environment requirements such as indoor environmental quality, insulation, comfort, structural integrity, and sustainability. The absence of MiC design codes and standards means that the completed projects may not meet the bespoke building regulatory requirement of a region. This could affect the value of the investment in terms of pricing and demand. The implication is that developers and clients must understand these regulatory risk factors before the implementation of MiC projects.

## Conclusions, contributions, limitations and future research

The unique planning, design, engineering, production, and installation of modular components in the MiC business model hatch different risk factors which may compromise the practical realization of project objectives. As MiC continues to become a preferred method of building construction, stakeholders require risk identification and assessment to ascertain the significant risk factors which may affect MiC projects. This study evaluated 29 risk factors in the implementation of MiC projects using a 5-point grading scale. A soft computing technique known as FSE facilitated objective analysis, assessment, and modelling of the subjective responses of experts from academia and industry in 18 countries and 6 continents. A mean score analysis generated 23 risk factors with mean scores above the critical threshold. Of these, the top 5 risk factors with significant impact include poor supply chain integration; higher initial capital cost; limited MiC expertise and experience; modular installation errors, complex rectifications and reworks; and stakeholder fragmentation and management complexity. A factor analysis of the 23 CRFs generated a 4-factor solution which clustered the risk factors into stakeholder and supply chain risks (PRF1); design and capabilities risks (PRF2); financing risks (PRF3); and regulatory risks (PRF4). The FSE analysis showed that all the factor groupings are critical with indices above the critical threshold of 3.0 on a 5-point grading scale. The FSE modelling ranked financing risks as the first and most critical; followed by regulatory risks ranking second; stakeholder and supply chain risks ranking third; and design and capabilities risks ranking fourth. A FSE model of the overall risk level generated an overall criticality index of 3.30, indicating that MiC projects have some significant risk and should be planned extensively before implementation.

The quantitative evaluation and ranking of the risk factors have useful practical and managerial implications in any MiC project. First, the paper accomplished the first three stages of risk management which include risk planning, identification, and assessment. Thus, it has screened the risk factors and identified the CRFs, which may significantly derail MiC project success. Although the magnitude of the impact of the risk factors differs across different MiC project types and territories, the identified CRFs may be further given detailed quantitative analysis to ascertain the most CRFs for a given MiC project and territory. This will allow for the efficient allocation of resources to improve the success of MiC projects. Indeed, the four PRFs identified in the research may serve as a basis for developing cost-effective risk management guidelines. Second, the risk assessment conducted in the current study may serve as decision support in investment planning and decision-making. It provides a preliminary basis to choose between MiC projects and deciding whether to invest in a given project based on the risk indices. Third, given the identified CRFs, stakeholders may assess their capabilities of managing the risk events during risk control and allocation.  Fourth, this research constitutes the first exclusive empirical multi-attribute objective risk assessment for MiC projects. The most significant risk factors identified may serve as a risk evaluation tool at the early stages of an MiC project where bespoke studies are unavailable or not feasible.

However, the results of the study must be examined against the following limitations. First, the risk factors evaluated in the current study were extracted from empirical studies in the literature and generalized. Stakeholders, researchers, and practitioners should recognize that MiC risk factors are sensitive to project types, countries, locations, and objectives. Thus, bespoke studies may have to be conducted to identify those risk factors relevant to a project and territory. Second, the analysis identified 6 risk factors as less critical but, these risk factors may constitute the critical risk factors in different contexts and should be included in initial risk assessment. Third, the study constitutes a global one but the sample size, although adequate may be considered small. The generalization may suffer from the limited sample size. However, such a sweeping generalization is useful for the theoretical progress of MiC risk management because it is often useful to overlook these project and geospatial sensitivities since they become absolutely essential when such generalized analysis is tailored towards a specific project for risk management. Third, the study implemented an FSE analysis of the risk factors, but the method has its own limitations. Future research may address this methodological limitation by using other methods such as structural equation modelling, artificial neural networks, systems dynamic, simulation, or fuzzy analytical hierarchy process to analyse data on the risk factors. The next stage of this research will develop a robust systems dynamic model of the risks factors to explore their interdependences and interactions.

## Data Availability Statement

Some or all data, models, or code generated or used during the study are available from the corresponding author by request (*Background information of the MiC experts and evaluation of the risk factors for MiC projects*)

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