Front. Eng. Manag. 2020, 7(1): 63–80
https://doi.org/10.1007/s42524-019-0059-7

REVIEW ARTICLE

**Ibrahim Yahaya WUNI, Geoffrey Qiping SHEN, Bon-Gang HWANG**

# Risks of modular integrated construction: A review and future research directions



**Abstract** Stakeholders remain skeptical in adopting modular integrated construction (MiC) because of the associated risks and uncertainties, although its benefits have been extensively documented. The unique business model of MiC nurtures several risks and uncertainties different from those of the conventional construction approach. Despite the growing attention on MiC with its market expansion, no systematic evaluation is in place to monitor its risks research progress. Accordingly, this research reviewed published literature addressing the risks associated with MiC from 1992 to 2019. Analysis reveals that the research publications on risks of MiC witnessed a steady growth, with considerable progress occurring in the last decade. Result implies that the risk of MiC has gained extra attention in the construction engineering and management domain in recent times. Existing empirical studies have focused heavily on perceived implementation risks, supply chain risks, schedule risks, investment risks, structural risks, ergonomic risks, and MiC risk management strategies, which indicate that MiC is associated with a host of risk events. The research further identified the critical risk events (CREs) in the application of MiC based on frequency of occurrence. The identified CREs contributes to the checklists of risk events in the implementation of offsite construction (OSC). The latter may be useful in risk planning, especially where the MiC is less developed, and fewer or no bespoke risk assessment exists. Research gaps in existing studies are highlighted in this research, and areas for further studies are then proposed. Thus, it makes a useful contribution to the scholarly literature on the risk of OSC and may prove useful to offsite construction researchers, industry practitioners, and project managers.

**Keywords** modular integrated construction, off-site construction, risk events, review

## 1 Introduction

Industrialized building construction is pursued to address the manifold ill performances of the traditional business model of the construction sector. Richard (2005) argued that industrialized construction could increase the efficiency and productivity of the construction industry, similar to those of the manufacturing industry. Offsite construction (OSC) is one of the approaches aimed at industrializing the construction sector. OSC is a construction production process, which shifts preponderances of the work packages in conventional construction method (CCM) to an offsite factory, resulting in the fabrication of building components, which are trucked to a jobsite for final assembly (Gibb, 2001). Modular integrated construction (MiC) is a distinctive form of OSC, where 80%–95% of an entire building can be manufactured in an offsite factory environment (Smith, 2016). MiC reduces construction time owing to the concurrent offsite and onsite activities, minimizes labor cost owing to the stable factory labor force, quickens the learning curve owing to the repetitive works (Murtaza et al., 1993), reduces project lifecycle cost (Blismas et al., 2006), improves project adaptability, supports change without demolition (Richard, 2005), reduces construction waste and water footprint

Received April 10, 2019; accepted July 28, 2019

Ibrahim Yahaya WUNI (✉), Geoffrey Qiping SHEN
Department of Building and Real Estate, The Hong Kong Polytechnic University, Hong Kong, China
E-mail: ibrahim.wuni@connect.polyu.hk

Bon-Gang HWANG
Department of Building, National University of Singapore, Singapore 117566, Singapore

This paper was fully funded under the Hong Kong Ph.D. Fellowship Scheme (HKPFS: PF17-00649) by the Research Grants Council of the Hong Kong Special Administrative Region, China. The paper constitutes a part of a Ph.D. research project currently being conducted at The Hong Kong Polytechnic University.

(Jaillon and Poon, 2008; Jaillon et al., 2009), and reduces toxic stratospheric gas emissions (Mao et al., 2013). Thus, MiC is a considered sustainable construction business model when well-implemented.

Owing to these benefits, models of MiC are promoted in Australia, Canada, USA, the UK, Singapore, Sweden, South Korea, China, and Malaysia such as off-site manufacture, modular construction, prework, off-site production, prefabricated prefinished volumetric construction, industrialized housing construction, and industrialized building systems. However, MiC is associated with unique processes and trades (Wuni et al., 2019a) resulting in considerable risks and uncertainties different from those of the CCM (Li et al., 2013). For example, the implementation of MiC requires modular design, manufacturing, transportation, storage, and jobsite installation. These distinct stages of the supply chain of MiC are currently fragmented but substantially interdependent, resulting in manifold uncertainties which could compromise the successful implementation of MiC projects (Li et al., 2016). As these linked segments constitute nearly a fixed and unique linear sequence with minimal overlapping, disturbances in upstream segments may affect the continuity of downstream segments or the entire supply chain (Wuni and Shen, 2019b). To illustrate, too early delivery of modular components requires storage space, whereas delays in transporting modular components to the jobsite may halt the entire installation process (Li et al., 2018a). Moreover, failure of modular production plants may directly translate into delays in modular delivery and subsequent shortage of modular components on the construction site because third-party modular manufacturers cannot complement the deficit with different components.

Again, problematic dimensional and geometric variabilities in modular elements in MiC projects abound and constitute recipes for defects and expensive reworks (Shahtaheri et al., 2017). The Bureau of Labor Statistics (2009) reported that construction workers in residential MiC projects in the USA are exposed to higher rates of injuries, accidents, and incidents, than the rates in the CCM. These uncertainties and risk events translate into barriers to the adoption of MiC as some of them are counterproductive to the benefits of the approach. Despite these uncertainties and risks events, MiC is gaining attention with its market expansion in the Architecture, Engineering, and Construction (AEC) industry. Recognizing risk as inevitable in construction projects (Baloi and Price, 2003), there is a growing body of studies seeking to understand the risks and uncertainties associated with MiC. However, a systematic review of these empirical studies has not been well established, although monitoring the progress of studies on the risk of MiC and bridging the gap between empirical studies and practical risk management are essential. Hosseini et al. (2018) conducted a scientometric review of studies on OSC, and Li et al. (2014) critically reviewed studies on the management of MiC projects. However, these studies were generic and offered very little or no documentation of the risks of MiC.

Thus, this research reviewed and synthesized published literature addressing the risks associated with MiC through the lens of the systematic review methodology. Specifically, this research aims to (1) examine the research publication trend on the risks associated with MiC, (2) identify emerging salient and topical areas on the risk of MiC, (3) highlight the critical risk events (CREs) in MiC, (4) propose a risk breakdown structure of MiC, and (5) highlight the areas requiring further studies. Accordingly, the research makes a useful contribution to the scholarly literature on OSC as it represents the first exclusive systematic review of the literature addressing the risks associated with MiC. Particularly, the research delineates the knowledge boundaries in existing studies, highlights some research gaps, and offers directions for future studies. It highlights some critical risk events in MiC, which contributes to the checklists of the risk events in OSC. They may also be prioritized in the implementation of MiC, especially in countries where bespoke MiC risk assessment is unavailable. A risk breakdown structure is also developed to offer a bird's eye view of the risk structure of MiC. As such, this research is relevant to OSC researchers, developers, project managers, teaching staff, policymakers, and industry practitioners. The rest of the paper is organized as follows. The next section presents an overview of MiC, followed by a description of the adopted research methodology. The review findings are presented in the fourth section, and the last section draws conclusions based on the findings.

## 2 Overview of modular integrated construction

Modular integrated construction (MiC) is an innovative construction method, whereby "free-standing integrated modules (usually completed with finishes, fixtures, and fittings) are manufactured in a prefabrication factory and then transported to site for installation in a building" (Construction Industry Council, 2018). Smith (2016) describes MiC as the most complete form of OSC. According to Gibb (1999), the MiC implementation involves four degrees of modularization comprising "components manufacture and subassembly, non-volumetric preassembly, volumetric preassembly, and an assembled modular building". Figure 1 shows the major stages in the modular integrated construction process.

The general delivery chain of MiC is often reified as modular engineering, design, manufacturing, transportation, storage, buffer, and onsite installation (Li et al., 2016). These processes involve several stakeholders, including

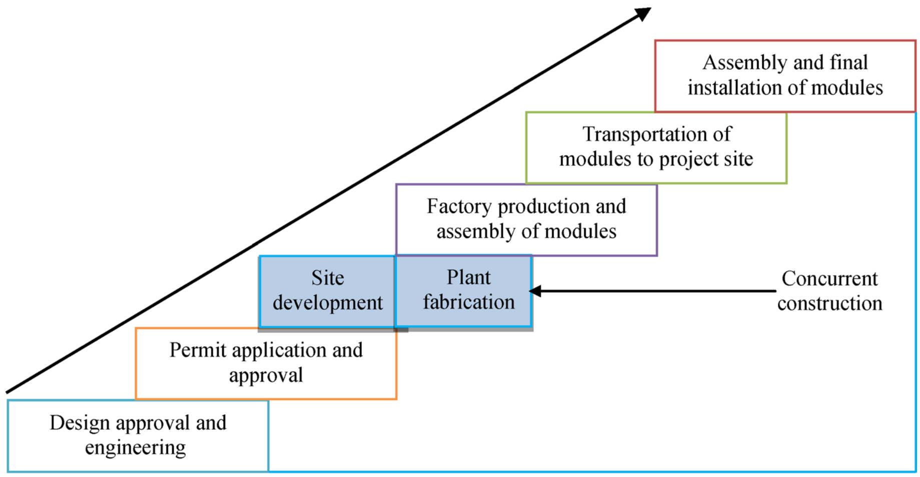


**Fig. 1** Stages of the modular integrated construction process.

main contractors, assembly subcontractors, manufacturers, suppliers, architects, engineers, site engineer, developers, housebuilders, designers, clients, consultants, academics, transporters, logistics managers, project coordinators, and local government (Li et al., 2016; Bortolini et al., 2019). Nam and Tatum (1997) described these stakeholders as leaders and champions of construction innovation. These multidisciplinary practitioners and professionals have different objectives, motives, and value systems along the MiC delivery chain, engendering increased complexity in coordinating and managing the spectrum of participants in a project (Luo et al., 2019).

MiC is an example of the design for manufacture and assembly (DfMA) philosophy (Construction Industry Council, 2018), and the production of modules often involves job-shop scheduling (Dawood, 1995a). Modular components are typically made-to-order and designed for exclusive usage in a specific project. As such, Hsu et al. (2018) noted that scheduling must be configured such that the optimum quantity of each module manufactured and transported to the site exactly meets its demand in a project and returns the inventory to zero upon completion to avoid wastage. Given this target, the onsite modular demand deficit cannot be satisfied by a third-party manufacturer. This unique production scheduling in the supply chain of MiC is different from the case of the CCM, resulting in layers of new uncertainties in the construction process. The resulting MiC project could be permanent or temporary (Smith, 2016). However, MiC generates flexible, industrialized, and demountable buildings rather than standardized “boxes”. Richard (2005) indicated that the goal of MiC is to manufacture industrialized building systems where the same design specifications generate highly individualized and customizable buildings, which can be situated in different areas. Models of MiC include prefabricated prefinished volumetric construction in Singapore, industrialized building systems in Malaysia, and PPMOF (prefabrication, preassembly, modularization, and off-site fabrication) in North America, and so on.

## 3 Research methods

This research adopted pragmatism as the research paradigm in reviewing published literature addressing the various risk facets of MiC. Pragmatism provides legitimacy and a framework for synthesizing both qualitative and quantitative empirical studies. Accordingly, the systematic literature review (SLR) methodology was deployed. SLR is a powerful scientific method, which adopts a systematic and objective protocol in synthesizing knowledge for a particular research domain (Webster and Watson, 2002). Considering the organic nature of literature in the construction engineering and management (CEM), SLR becomes a powerful tool for delineating the boundaries of the scientific knowledge in a given research domain (Wuni et al., 2019a). As such, this research adopted a 4-stage SLR methodology to review published literature addressing the risks associated with MiC comprising comprehensive literature search, rapid and full-text evaluation, meta-synthesis, and content analysis.

### 3.1 Database selection and literature search

An SLR must be underpinned by a thorough and unbiased search for relevant studies (Evans, 2004). This research initiated the search process by specifying databases rather than journals to ensure a broad coverage of the relevant studies. The authors examined Scopus, Google Scholar, Web of Science, Science Direct, and Engineering Village to identify the one with the widest coverage. Preliminary searches revealed that preponderances of the published literature have been contemporaneously indexed in the adumbrated literature databases. However, as noted in a recently published review study (Wuni et al., 2019b), this research found Scopus to have the widest coverage and easy-to-conduct structured queries. As such, Scopus was adopted in the literature retrieval process. Prior to the search query in Scopus, synonyms for "risk" and "MiC" were extracted from published studies. The authors continuously updated the search string throughout the review process to ensure the widest possible coverage. The full search string used for retrieval of the relevant articles is given below.

[TITLE-ABS-KEY (risk OR hazard OR uncertainty OR uncertainties OR safety OR delay OR "cost overrun" OR "time overrun") AND TITLE ("offsite construction" OR "off-site construction" OR "offsite production" OR "off-site production" OR "offsite manufacturing" OR prefabrication OR prefabricated OR prefab OR pre-fabricated) OR TITLE ("industrialized building system" OR "modular construction" OR modular OR "precast construction" OR "off-site fabrication" OR "prefabricated prefinished volumetric construction" OR "modern method of construction" OR "industrialized construction") AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "ip")) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (SRCTYPE, "j"))]

After noting the spelling variations during the review process, some keywords for MiC were repeated in the algorithm but spelled differently. The algorithm is a structured but constrained search string. As shown in the algorithm, only Articles and Articles in Press were retrieved; thus, the search was limited to only Journals. In addition, only English-Language publications were included. These filters generated 1164 Scopus records (as of 15 February 2019), and they were screened to identify relevant articles. Moreover, the search algorithm was re-executed (9 April 2019) to identify newly published studies before submission. The final search retrieved three more published studies, which were screened and considered.

### 3.2 Inclusion and exclusion criteria

Inclusion and exclusion criteria constitute the benchmarks used in an SLR for filtering the actual sample size from the universe of articles in search queries (Wohlin, 2014). Consequently, this research developed some inclusion and exclusion criteria to evaluate the retrieved published literature. Specifically, only empirical studies addressing the risks associated with MiC and published in peer-reviewed research outlets were included. The research excluded conference papers owing to common censure that they are not subjected to a rigorous peer-review process. Articles were selected on the basis of metadata (title and abstracts) screening and full-text evaluations.

Following a rapid screening of the 1164 Scopus records, 125 articles were deemed valid for full-text evaluations. The authors found and included 38 relevant articles following the full-text evaluation. Figure 2 presents the systematic literature search, screening, and selection process. Although the sample size (38) compares favorably with published reviews, which analyzed 16 and 32 articles (Newaz et al., 2018; Saieg et al., 2018), respectively, the snowballing search strategy was adopted to further locate relevant articles.

The "snowballing" search strategy was adopted as Wohlin (2014) noted the limitation of exclusively using algorithm-driven search string; indeed, specifying exhaustive keywords in the search string is impractical. Snowballing search refers to a strategy of using reference lists and citations of a paper to locate additional studies (Wohlin, 2014). It involves searching the references (backward snowballing) and tracking the citations (forward snowballing) of an article to locate additional studies. Based on the recommendations of Levy and Ellis (2006) and Wohlin (2014), the 38 articles constituted the sample set for the snowballing search. The authors conducted backward and forward snowballing searches using these articles. Given the iterative nature of the snowballing search, Webster and Watson (2002) and Levy and Ellis (2006) suggested that the search should be aborted when (i) new findings are not emerging from the newly retrieved articles, (ii) no different citations are discovered in the newly retrieved articles, and (iii) the articles cited in newly retrieved articles have been evaluated. Thus, the authors aborted the iterative search based on these principles. This process resulted in the inclusion of 16 additional relevant articles, thereby increasing the actual sample size to 54. Table 1 shows a bibliographic summary of the included studies.

### 3.3 Meta-synthesis and content analysis

The research adopted meta-synthesis as the organizing framework for extracting and integrating the metadata of the 54 empirical studies. Meta-synthesis is a mixed method of conducting SLR, which draws on both qualitative and quantitative studies (Baker, 2016). It starts with the specification of units of analyses and extraction of metadata (Finfgeld-Connett, 2014). The year of publication, journal name, research focus, and limitations of each study were extracted and cataloged. These details were organized into an Excel file as a summary table. Webster and Watson (2002) described this summary table as a "concept matrix augmented with units of analyses". A systematic approach was further used to cluster the studies into various research themes based on the emphasis of each study. This method is described as a content analysis

**Table 1** Bibliographic summary of the included studies

| S.N. | Reference | S.N. | Reference |
|---|---|---|---|
| 1 | Gustavsson et al. (1992) | 28 | Li et al. (2017a) |
| 2 | Dawood (1995a) | 29 | Li et al. (2017b) |
| 3 | Dawood (1995b) | 30 | Li et al. (2017c) |
| 4 | Gibb and Neale (1997) | 31 | Love et al. (2017) |
| 5 | Chiang et al. (2006) | 32 | Salama et al. (2017) |
| 6 | Hassim et al. (2008) | 33 | Shahtaheri et al. (2017) |
| 7 | Polat (2008) | 34 | Jiang et al. (2018b) |
| 8 | Hassim et al. (2009) | 35 | Xue et al. (2017) |
| 9 | Nahmens and Ikuma (2009) | 36 | Jiao and Li (2018) |
| 10 | Blismas and Wakefield (2009) | 37 | Jiang et al. (2018a) |
| 11 | Kim et al. (2011) | 38 | Lin et al. (2019) |
| 12 | Ikuma et al. (2011) | 39 | Li et al. (2018a) |
| 13 | Kim et al. (2012) | 40 | Li et al. (2018b) |
| 14 | Azman et al. (2013) | 41 | Havinga and Schellen (2018) |
| 15 | Chiu et al. (2013) | 42 | Hwang et al. (2018) |
| 16 | Li et al. (2013) | 43 | Ji et al. (2018) |
| 17 | James et al. (2014) | 44 | Gan et al. (2018) |
| 18 | Rahman (2014) | 45 | Hsu et al. (2018) |
| 19 | Zhai et al. (2014) | 46 | Taghaddos et al. (2018) |
| 20 | Mao et al. (2015) | 47 | Xue et al. (2018) |
| 21 | Luo et al. (2015) | 48 | Wang et al. (2018a) |
| 22 | Li et al. (2016) | 49 | Wang et al. (2018b) |
| 23 | Segura et al. (2016) | 50 | Li et al. (2019) |
| 24 | Adekunle and Nikolopoulou (2016) | 51 | Luo et al. (2019) |
| 25 | Fard et al. (2017) | 52 | Wu et al. (2019) |
| 26 | Hong et al. (2017) | 53 | Bortolini et al. (2019) |
| 27 | Lee and Kim (2017) | 54 | Enshassi et al. (2019) |

(Finfgeld-Connett, 2014). It provides an organizing framework to identify emerging trends from a corpus of texts. The research drew on the content analysis to identify the topical research clusters in previous studies and served as reference to develop the current and future research framework.

## 4 Findings and discussion

### 4.1 Annual research publication trend on the risks of MiC

The reviewed and synthesized studies covered the period of 1992 to 2019, although no "date range" restriction was specified during the search. This outcome suggests that the risk of MiC has been recognized in the CEM field since the last three decades. Figure 3 shows the annual research publication trend on the risks of MiC from 1992 to 2019. No trend is observed between 1992 and 2009 because only an average of one article was published annually. However, the period 2009–2019 recorded a steady growth of publications on the risks of MiC. Notably, the highest number of articles (14) was recorded in 2018. This finding was expected because the last decade witnessed a renaissance of the OSC movement and a concomitant renewed commitment to the promotion of MiC in many countries (Wuni and Shen, 2019a). The rising trend highlights the increasing attention given to the risk of MiC in the AEC industry (Li et al., 2014). As such, this study is timely and useful because when risks become a reality, they can derail the performance of MiC projects (Baloi and Price, 2003; Jiang et al., 2018a).

### 4.2 Journal distribution of the included studies

The included studies were published in 27 journals. Table 2 shows the journals, which have published studies addressing the risks associated with MiC. Analyzing the journal distribution of the reviewed studies offers a cursory view of the quality of studies included in the review and

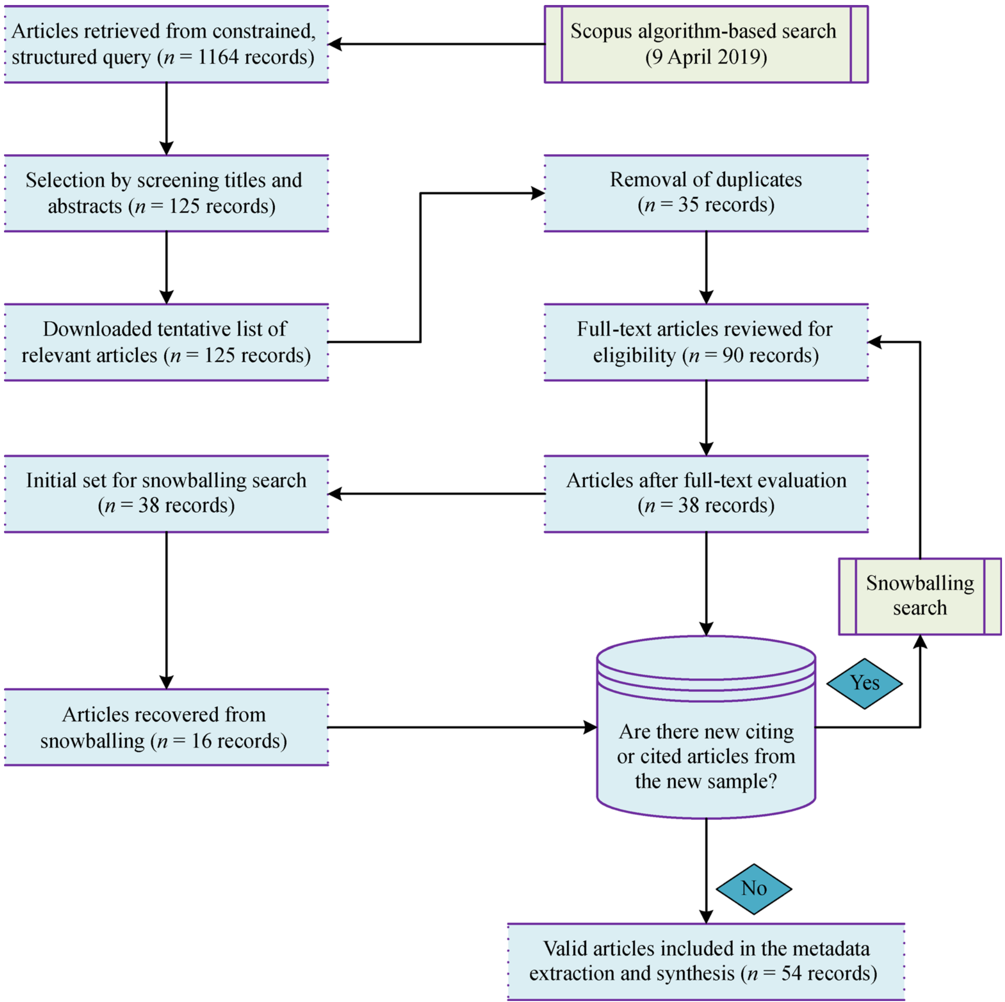


**Fig. 2** Flowchart of the systematic literature retrieval, screening, and selection procedure.

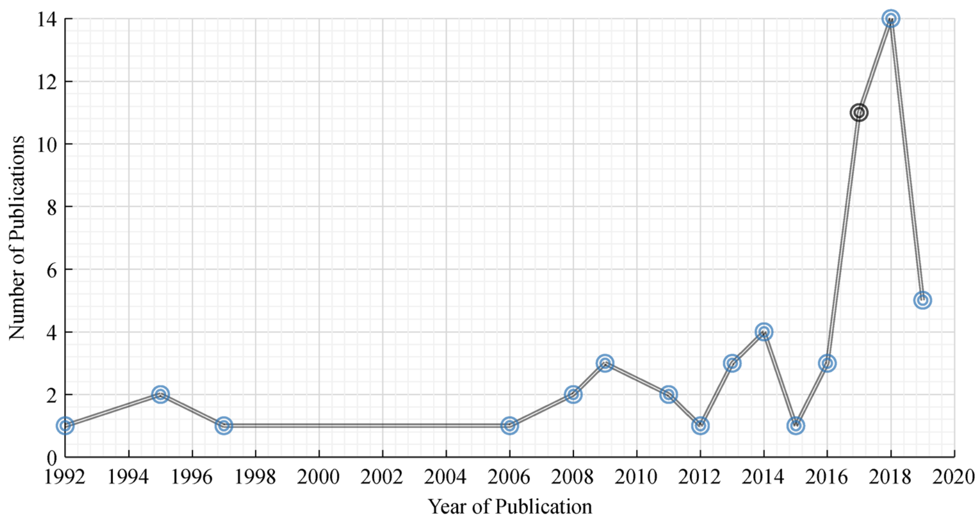


**Fig. 3** Annual publication trend on the risks associated with MiC from 1992 to 2019.

**Table 2** Active journals on the risk of MiC studies

| Name of Journal | Number of Articles ($N = 54$) |
|---|---|
| *Journal of Cleaner Production* | 11 |
| *Automation in Construction* | 7 |
| *Journal of Management in Engineering* | 4 |
| *Building and Environment* | 3 |
| *Journal of Construction Engineering and Management* | 3 |
| *Journal of Architectural Engineering* | 2 |
| *Journal of Civil Engineering and Management* | 2 |
| *Construction Management and Economics* | 2 |
| *Sustainability* | 2 |
| *Construction Innovation* | 1 |
| *American Journal of Applied Sciences* | 1 |
| *Applied Sciences* | 1 |
| *Archives of Civil Engineering* | 1 |
| *Buildings* | 1 |
| *Canadian Journal of Civil Engineering* | 1 |
| *Engineering, Construction, and Architectural Management* | 1 |
| *Ergonomics* | 1 |
| *European Journal of Social Sciences* | 1 |
| *American Journal of Industrial Medicine* | 1 |
| *Habitat International* | 1 |
| *The International Journal of Advanced Manufacturing Technology* | 1 |
| *Lean Construction Journal* | 1 |
| *Applied Ergonomics* | 1 |
| *International Journal of Injury Control and Safety Promotion* | 1 |
| *Journal of Performance of Constructed Facilities* | 1 |
| *KSCE Journal of Civil Engineering* | 1 |
| *Soil Dynamics and Earthquake Engineering* | 1 |

provides useful submission reference for researchers who conduct studies on the risks of MiC. Among the 27 journals, 9 contributed at least two articles. These journals included *Journal of Cleaner Production* (20.4%), *Automation in Construction* (13.0%), *Journal of Management in Engineering* (7.4%), *Building and Environment* (5.6%), *Journal of Construction Engineering and Management* (5.6%), *Journal of Architectural Engineering* (3.7%), *Journal of Civil Engineering and Management* (3.7%), *Construction Management and Economics* (3.7%), and *Sustainability* (3.7%). These journals cumulatively published 36 (66.7%) of the 54 reviewed articles.

Given the environmental friendliness of MiC (Quale et al., 2012; Mao et al., 2013), a superior contribution made by the *Journal of Cleaner Production* is not surprising because sustainability is one of its core missions. MiC also improves automation in the construction process (Richard, 2005; Shahtaheri et al., 2017). Thus, a high number of the articles published in A*utomation in Construction* is justifiable. Finally, articles related to ergonomic exposure and risks of work-related musculoskeletal disorders (WMSDs) (Kim et al., 2011), low back injury (Kim et al., 2012), and safety of construction workers in MiC projects (Fard et al., 2017) were published in journals such as *Ergonomics*, *Applied Ergonomics*, and *International Journal of Injury Control and Safety Management*, respectively.

### 4.3 Analysis of the salient research topics in existing studies

The subjectivity associated with the classification of studies into major research areas is recognized. However, it was observed that preponderances of existing research treatises identified and assessed risk events in MiC. The studies were mainly distinguished by the category of risks the authors investigated. Clustering the studies based on the forms of risks was deemed prudent. Despite the usefulness of such classification, it serves as reference only. Some articles discussed more than one identified theme and in such a case, the paper was classified according to the best-fit research area. The content analysis revealed seven major research themes, namely, (i) implementation risks, (ii) supply chain risks, (iii) schedule risks, (iv) investment risks, (v) structural risks, (vi) ergonomic risks, and (vii) risks management strategies. Table 3 shows the seven major themes, the associated sub-themes, and percentages of the articles addressing each theme.

#### 4.3.1 Implementation risks

MiC is innovatively disruptive because it engenders profound changes to the entrenched conventional construction project design, engineering, scope, and processes (Slaughter, 1998). These changes introduce new layers of uncertainties in the construction process and expose decision-makers to new challenges (Luo et al., 2015). As an innovative method, MiC is facing a strong resistance from industry practitioners given the need required to change entrenched construction practices (Lovell and Smith, 2010). Stakeholders stereotype MiC as a risky approach owing to a perceived increased complexity in project delivery resulting from the manifold trades and stakeholders to be coordinated (Xue et al., 2018; Lovell and Smith, 2010). Hassim et al. (2008) found that contractors in Malaysia attributed the perceived riskiness of MiC to insufficient experience, design complexity, and contractor performance failure. Hassim et al. (2009) also reported that work changes, defective design, changes in government regulation, contractor inexperience, and payment problems represent the top five sources of risks for MiC projects in Malaysia. Some of these risk perceptions

**Table 3** Percentages of papers addressing the seven major research themes

| Research theme | Sub-themes | % of papers |
|---|---|---|
| Implementation risks | MiC adoption risks, risk perceptions, sources of risks, implementation uncertainties, perceived barriers, project failures, MiC project management problems | 9 |
| Supply chain risks | Stakeholder management risks, fragmented and complex network of stakeholders, complex coordination of supply chain stages, supply chain management constraints, complexity in optimal supply chain configuration, supply chain disturbances | 19 |
| Schedule risks | MiC project delays, modular component delivery delays, scheduling uncertainties, schedule delay risk events, component assembly challenges | 10 |
| Investment risks | High setup capital, long break-even periods, market demand for modular homes, volatile economic conditions, public consumption habits | 6 |
| Structural risks | Complexity in structural design for high-risk MiC projects, structural integrity issues, vertical connections of modular components, complex multi-interfaces, dimensional and geometric tolerances, multi-hazard design, stable seismic performance, structural resilience, gravitational load of floor slabs, eccentricities, deterioration of components, dampness | 13 |
| Ergonomic risks | Health and safety of factory workers, fall injuries, low back pains, awkward working postures, spinal comprehensive and shear forces, fatigue, work-related musculoskeletal disorders | 15 |
| Risks management strategies | Time and space hedging, integrated building information modeling platforms, smart construction monitoring, integrated project delivery, stakeholder collaborative management, optimal supply chain configuration, tolerance risk management, automated ergonomic risk management, lean production and management | 28 |

(e.g., complex project delivery) may be due to inexperience and insufficient knowledge of the MiC business model, because the approach aims to simplify the construction process by streamlining and structuring both the on-site and off-site work packages (Richard, 2005).

Notwithstanding, Nussbaum et al. (2009) opined that MiC is associated with manifold risks and uncertainties owing to the complex parade of trades and extensive fragmented discrete events. Luo et al. (2015) reported that poor cooperation among multi-interface, inadequate design codes and standards, lack of best management practices, high initial capital cost, and lack of quality monitoring mechanisms constitute the five critical risk factors that breed the reluctance to adopt MiC in China. Given that the MiC industry remains in the fledgling stage in some countries (e.g., China), Jiang et al. (2018a) found the failure of demonstration projects, limited capacity of modular manufacturers, and inexperience account for the perceived riskiness of MiC. These risk perceptions render MiC unattractive to stakeholders.

### 4.3.2 Supply chain risks

The supply chain of MiC comprises the design of modules, engineering, manufacturing, transportation, storage, and onsite installation. These segments are linked but currently fragmented, hatching uncertainties at each level of the continuum (Li et al., 2013). Hwang et al. (2018) stated that the implementation of MiC demands extensive synchronization of the various supply chain segments and associated stakeholders before and during the construction process. Several decisions and tradeoffs are made under uncertainties at various segments of the supply chain. At the initial design phase, the justification to apply MiC in a project is grounded on multiple factors, which are also project- and context-dependent (Murtaza et al., 1993). For example, the decision to adopt MiC in the One Ludgate Place in London was based on cost, time, past experience, design, structural interface, weather joints, performance tests, site logistics, and safety (Gibb and Neale, 1997); whereas a decision to apply MiC in a power plant project was based on plant location, labor, environmental consideration, project characteristics, and risk profile (Murtaza et al., 1993). These differences in decision factors introduce bespoke uncertainties, which are unique to a project during the feasibility and economic analysis. Nonetheless, early decisions are indispensable at the conceptual design stage of MiC projects because implementing changes is obscure during construction (Shahtaheri et al., 2017).

Again, modular manufacturing operations are often based on engineer-to-order owing to the uniqueness of each MiC project (Bortolini et al., 2019). The bidding decisions of modular manufacturers require precise valuation of the optimal mark up on price based on design and production planning of every MiC project (Dawood, 1995b). Such decisions are made in the context of uncertainties. Even the selection of a location for a modular production factory depends on multiple factors, such as costs, transportation, land accessibility, availability of raw materials, and infrastructure (Azman et al., 2013). Essentially, optimal configuration of the entire supply chain is required to minimize extreme uncertainties, disruptions, and disturbances during the construction process (Shahtaheri et al., 2017). Given that modular components are specific to a project and made-to-order, logistical planning in MiC must ensure that the quantity of components produced in a factory precisely matches the onsite modular demand, allowing the inventory to become empty upon completion of the project (Hsu et al., 2018). This unique scheduling and procurement configuration requires the consideration of multiple schedule deviation factors and disturbances along the entire supply chain. Considering the interdependences of the various segments of the supply chain (Li et al., 2018a), disturbances within one segment could disrupt other supply chain segments. For example, modular production system failure and defects in modular components may halt the onsite installation process, especially when there is no safety stock (Wang et al., 2018a). Pronounced impacts of these supply chain disturbances are expected because their causes cannot be anticipated until they occur (Wang et al., 2018a).

Furthermore, the MiC supply chain is dominated by multidisciplinary stakeholders, such as designers, architects, engineers, manufacturers, transporters, logistics managers, main contractors, assembly subcontractors, site engineers, and local authorities (Luo et al., 2019). Each practitioner or stakeholder has an exclusive motive and value system in an MiC project. Coordination of these disparate, sometimes conflicting, requirements and interests of the multiple involved parties introduces new layers of uncertainties and risks in the construction process (Li et al., 2017a). The fragmented and complex MiC stakeholder composition may result in poor resource planning and scheduling, workflow control, and information sharing among project stakeholders (Luo et al., 2019). For example, the separate dominance of different stakeholders in the planning and control of each of the linked supply chain segments may increase the lead time of MiC projects (Bortolini et al., 2019). Again, failure in upstream segments of the supply chain has detrimental implications on the reliability of downstream segments.

#### 4.3.3 Schedule risks

Project delay occurs when a completion date of a project extends beyond the stipulated contractual duration (Assaf and Al-Hejji, 2006). Project delays are inevitable in the construction sector (Egan, 1998). Ji et al. (2018) found that inadequate worker experience, inefficient modular component connection, poor stakeholder management, and low productivity constitute some of the most critical causes of delays in MiC projects. Li et al. (2018a) found that the chief trigger of delays in MiC projects is supply chain disruptions. Given that modular components are made-to-order, modular production often requires job shop scheduling to optimize the allocation of resources and facilitate timely modular delivery (Dawood, 1995a). However, job shop scheduling is sensitive to fluctuations in sales, cost, volume of modules, cost of changeovers, margins of profit, and curing time (Dawood, 1995a). These variabilities also depend on modular plant characteristics, attributes of modules, scheduling shift patterns, demand forecast, and dispatch information (Dawood, 1995a). Effectively, these variations nurture multiple uncertainties and risks in the modular scheduling process. Beyond the scheduling stage, several events are known to generate delays in the schedules of MiC projects. For instance, wind disruptions resulted in a lost time of 18 days during the installation of complex prefabricated cladding in the One Ludgate Place in London (Gibb and Neale, 1997).

Similarly, Hsu et al. (2018) found that weather disruptions, delays in modular delivery, and crane failure caused delays in the schedule performance of some MiC projects in the UK. Moreover, inefficient design approval, ineffective design data transition, inefficient verification of modules, delays in modular delivery, design information gap between designer and manufacturer, low information interoperability among different information management tools, modular installation errors, and tower crane malfunction were found to be the most critical schedule delay risk factors in residential MiC projects in Hong Kong (Li et al., 2018a). Li et al. (2018c) found that these supply chain ill-performances resulted in 200–300 min delays in the six-day cycle assembly of prefabricated housing construction in Hong Kong. Therefore, several events may cause schedule delays in MiC projects and careful consideration in the MiC program is required.

#### 4.3.4 Investment risks

Applying MiC in a project requires reliable production and supply of modular components. Thus, the adoption of MiC in a country requires significant investment from stakeholders. Huge capital is necessary to purchase land for the offsite factory, manufacturing plant, production equipment, raw materials, and labor (Zhang et al., 2014). The capital-intensive profile of MiC exposes investors to manifold uncertainties and risks, as several years may be needed to break even. Studies have identified some MiC investment risk factors. In China, Li et al. (2017c) found that the high price of modular components, conservative public consumption habit, inadequate modular codes, and lack of cutting-edge modular production technologies engender significant risks to investment in MiC projects. Li et al. (2013) found that volatile economic conditions and sociopolitical climate are the most important investment risk factors in Canada. Lee and Kim (2017) identified insufficient modular design expertise, poor cost estimation, unstable modular production rate, and errors in structural designs to be the most critical risk factors, which trigger cost increase in MiC projects in South Korea. Essentially, critical investment risk factors differ across countries and projects. However, MiC is associated with a host of investment risk factors. Particularly, investors may take a long period to break even or achieve commensurate returns on the high initial capital investment, especially in countries where the MiC market is at the fledgling stage (Dawood, 1995a; Richard, 2005).

#### 4.3.5 Structural risks

Climate change-driven hazards, such as typhoons, earthquakes, progressive collapse, landslides, cyclones, flooding, and severe marine environment, are changing the structural requirement of construction projects (Lin et al., 2019) and have spurred research on structural risks in the construction and civil engineering domains. The higher complexity in structural design for high-rise MiC projects that can accommodate strong wind load constitutes a significant challenge in high-density cities and neighborhoods (Wuni et al., 2019a). The structural integrity of MiC projects is paramount to overcome the historic stigma associated with the hastily implemented post-war prefabricated buildings, such as the 1968 collapse of the 22-story Ronan Point Apartment Tower in East London. Structural integrity and operational capability of MiC projects exert influence on cost, quality, and satisfaction of clients (Shahtaheri et al., 2017). However, owing to the complex multi-interfaces in MiC projects, intolerances of modular components engender defects in MiC projects and render these projects vulnerable to structural failure (Gibb and Neale, 1997; Shahtaheri et al., 2017).

Shahtaheri et al. (2017) noted that amid the precise methods of modular production (e.g., 3D fixturing, laser cutting, and robotic assembly) and cutting-edge modular inspection technologies (e.g., laser scanning), problematic dimensional and geometric variabilities abound in MiC projects owing to modular geometric conflicts during production and between modules and site interfaces. In addition, incompatibility between process capabilities and desired levels of tolerance triggers a significant challenge in dealing with the excessive geometric variability risks in modular components and assembly (Enshassi et al., 2019). The accurate specification of allowable tolerances in MiC projects is indispensable because imprecision may result in less clemency between manufacturing and onsite erection tolerances (Enshassi et al., 2019). Dimensional and geometric tolerances in MiC are sensitive to modular production errors, the variability of components, measurement imprecision, and discrepancies among modular interfaces. Thus, failure to specify allowable variability and control tolerances could incubate an obligatory need for reworks (Shahtaheri et al., 2017). Existing geometric variability management practices mostly involve trial and error solutions, ad hoc strategies, and the application of strict tolerances, which have often resulted in quality problems, schedule delays, budget overrun, and increased site-fit reworks (Shahtaheri et al., 2017; Enshassi et al., 2019). Optimum geometric variability solution may require the combination of relaxed and strict tolerance approaches to minimize quality and problematic dimensional tolerances (Enshassi et al., 2019).

During the onsite assembly process of multi-story MiC projects, some events occur, which may breed detrimental eccentricities. Construction errors and gravitational load of floor slabs are recipes for eccentricities, which could complicate the installation of upper floors (Hong et al., 2017). These complications translate into low productivity, schedule delays, and cost overruns. Thus, selecting an effective modular connection method is required to avoid eccentricities. Lin et al. (2019) noted that the structural performance and safety of high-rise MiC projects could be enhanced if these projects are designed to be multi-hazard resistant. Seismic actions and progressive collapse require critical consideration (Chiu et al., 2013; Lin et al., 2019). The multi-hazard design (structural seismic + progressive collapse design) is required to resist lateral forces from seismic actions and unbalanced vertical loads induced by localized failure (Lin et al., 2019). The multi-hazard MiC project should achieve stable seismic performance, structural resilience, and infinitesimal deformation following hazards (Lin et al., 2019).

Moreover, studies have explored the structural risk of MiC projects at the operation stage. Segura et al. (2016) reported that a cooling tower for a thermal power plant constructed with precast concrete suffered a severe deterioration within three years of service life following a severe exposure to marine conditions. Although the early deterioration was associated with the wetting–drying cycles and chloride-induced corrosion, it demonstrates the potential weaknesses of MiC under severe marine conditions. Adekunle and Nikolopoulou (2016) found that 67% of 116 modular (timber) houses in the UK suffered poor indoor thermal conditions and summertime overheating. Apparently, the low thermal mass of timber exposes such houses to the risk of summertime overheating. Havinga and Schellen (2018) reported mold growth and condensation in 144 Airey houses in the UK amid the internal insulation. This finding highlights the need for a careful selection of insulation materials for panelized residential MiC projects to prevent early deterioration. Jiao and Li (2018) also reported severe dampness in the external walls of MiC projects in China.

#### 4.3.6 Ergonomic risks

Construction is generally a risk activity, which exposes its workforce to several health threats from potential falling and awkward working postures (Newaz et al., 2018). In fact, a high incidence of fall injuries, low back pains, and risk of WMSDs are common among construction workers (Bureau of Labor Statistics, 2009; Valero et al., 2016). Owing to the controlled factory environment, reduced onsite activities, few construction workers on site, and the minimized requirement to work from heights, MiC improves the safety and health of construction workers (Blismas et al., 2006; McGraw Hill Construction, 2013). In a survey, the majority of general and specialty contractors in the UK indicated that MiC have improved the safety performance of projects (McGraw Hill Construction, 2013). However, the Bureau of Labor Statistics (2017) reported that the total injury and incidence rate (10.2 per 100 workers) was higher in manufactured housing compared with the rate (5.2 per 100 workers) in the onsite residential construction, and both were above the national average of the USA at 4.2 per 100 workers. In lean construction parlance, poor safety constitutes a substantial cost owing to human suffering, compensation cost of workers, lost productivity, and high employee turnover (Nahmens and Ikuma, 2009).

Different construction workers are exposed to safety risks at various segments of the MiC supply chain. Gustavsson et al. (1992) reported that 16 of 1068 workers exposed to artificial mineral fibers, asbestos, combustion fumes from furnaces, and arsenic in a Swedish manufactured housing factory died of lung cancer. In the USA, construction workers in a modular home manufacturing plant sustained several injuries following exposure to sawdust, excessive noise and volatile organic compounds, and forceful exertion during the cutting and assembly of heavy components (Ikuma et al., 2011). Similarly, Kim et al. (2011) found that construction workers were subjected to awkward working postures during the erection of prefabricated panelized wall systems as they exceeded their comprehensive action limits for the spine (34%) and shear forces (77%).

These ergonomic exposures and biomechanical risk events abound because construction workers still engage in the manual (team) handling of modular components, such as wall panels in residential MiC (Kim et al., 2012). Although manual handling is appropriate where mechanical aids are unfeasible, the heavy masses of modular components engender risks to the safety of the workers. Nussbaum et al. (2009) found that residential carpenters in the manufactured housing in the USA were involved in the lifting, carrying, and erecting of panelized walls in the range of 1.2–6.0 m wide and approximately 250 kg. These tasks exposed the workforce to fall injuries, arm, lower, and upper back pains (Nussbaum et al., 2009). Similarly, Fard et al. (2017) found that out of 125 accidents during modular production and onsite installation, hospitalized injuries (50.4%), fatalities (38.4%), and non-hospitalized injuries (11.2%) mainly resulted from falls and being struck by construction objects. Essentially, the manual handling and operations during modular production and on-site assembly are the recipes for the safety risks. Hsu et al. (2018) found that construction workers in the UK reported severe fatigue as they manually inspected, unpacked, lined up, unfastened, screwed, and welded modules, and enabled crane lift upon the arrival of modules to a construction site.

### 4.4 Critical risk events in the implementation of MiC

Following risk identification and assessment, the next level on the risk management hierarchy is risk prioritization (Project Management Institute, 2017). Risk events abound in MiC projects, but their impact varies. Dealing with all risk events is uneconomical and impractical. Thus, risk management often prioritizes the critical risk events as they can derail the performance of projects. The CREs are the risk events with the most "violent or aggressive" impact on MiC projects' objectives. Table 4 shows the 19 most cited risk events. This study recognizes the necessity for a quantitative assessment to identify the CREs and that the CREs would differ across countries and projects. However, the CREs in this study represents risk events, which were frequently cited and reported in the literature. The frequency column of Table 4 depicts the number of articles that reported the associated risk event. These risk events were extracted and synthesized while conducting the full-text evaluation and review of the included studies. The rank of each individual risk event is based on the number of times (frequency) it was cited in the literature.

### 4.5 Risk management strategies

Several studies proposed strategies to avoid, reduce, or mitigate the impact of some of the MiC risk events discussed in the previous sections. However, presenting a risk structure of MiC before synthesizing the risk management strategies is useful. One useful tool in facilitating the comprehensive management of risk is the Risk Breakdown Structure (RBS). RBS depicts a hierarchical structure of the risks associated with a project. Figure 4 shows the RBS of MiC based on the review. For simplicity, only two levels are presented to illustrate the risk associated with the approach and its business model.

To address the supply chain and schedule risk events, Zhai et al. (2015) proposed lead-time (L), space (S), and L + S hedging techniques to create a buffer against unforeseen delays, upstream supply, and modular delivery uncertainties. These hedging techniques aimed at improving the reliability of modular supply to reduce schedule delays. However, as modules are made-to-order (Bortolini et al., 2019), advance production, transshipping, and dual sourcing of components in MiC are less feasible owing to its fixed supply chain once scheduled (Shahtaheri et al., 2017). Li et al. (2017b) demonstrated how radio frequency identification (RFID) and building information modeling (BIM) could manage and mitigate schedule risk events. They proposed an RFID-enabled real-time BIM platform, which integrates all relevant stakeholders in the MiC supply chain to allow for information sharing. The

**Table 4** Primary risk events in the implementation of MiC

| Risk event | Freq. | Rank |
|---|---|---|
| Delay in modular component delivery | 9 | 1 |
| Supply chain disruptions and disturbances | 9 | 1 |
| Inefficient scheduling | 8 | 3 |
| Defects in design, change order, and change in project scope | 7 | 4 |
| Complex stakeholder composition | 6 | 5 |
| Crane breakdown and malfunction | 6 | 5 |
| Insufficient information coordination among project participants | 6 | 5 |
| Modular installation error | 6 | 5 |
| Weather disruptions | 6 | 5 |
| Exposure to fumes, noise, and toxic compounds in modular production plant | 5 | 10 |
| Flexing, warping, and damage from transportation and handling | 5 | 10 |
| Manual inspecting, unwrapping, lining up, unhooking, screwing, and welding of modular components | 5 | 10 |
| Modular production materials and component shortages | 5 | 10 |
| Insufficient capacity of modular manufacturers and suppliers | 4 | 14 |
| Complex interfacing between modules | 3 | 15 |
| Geometric conflicts between components during manufacturing and between modules and site interfaces | 3 | 15 |
| Long distance between modular production plant and construction site | 3 | 15 |
| Dimensional and geometric variabilities | 3 | 15 |
| Modular production system failure | 2 | 19 |

platform enables real-time information interoperability, visibility, traceability, and exchange. Thus, the platform facilitates proactive risk management because stakeholders can monitor progress at all levels and could initiate timely measures to control latent events, which could cause schedule delays (Li et al., 2017a).

However, these information-driven strategies must move in tandem with other strategies to improve schedule performance. Wu et al. (2019) proposed the adoption of the integrated project delivery (IPD) approach (e.g., design–build model) to diffuse the fragmentation of the MiC supply chain and stakeholders because IPD demands multi-stakeholder collaboration (e.g., design–build team). Stakeholder collaborative management has a direct positive link with MiC projects' cost performances (Xue et al., 2018). Bortolini et al. (2019) found that collaborative planning enhances logistics management. In addition, Hsu et al. (2018) proposed an optimal supply chain configuration to account for onsite modular demand variations. The model aims to reduce production, operational, and penalty costs by determining the optimal supply chain configuration based on all possible demand profiles. The optimal configuration makes a warehouse an obligatory buffer and decoupling unit between the modular manufacturing plant and the jobsite (Hsu et al., 2018).

Toward improving the engineer-to-order manufacturing process, Wang et al. (2018b) proposed an optimization of the modular production scheduling based on operational uncertainties, such as process-waiting time on the flow of work, processing time uncertainty, and resources constraints. The optimization aims at generating minimal manufacturing cost, timely delivery of modules, and minimal resource wastage (Wang et al., 2018b).

In the context of structural risk, studies have proposed strategies to minimize dimensional intolerances. According to Salama et al. (2017), modular manufacturers should select an optimized configuration of modular components based on the limitations of onsite connection, transportation, and weight. The aim is to minimize the intolerance during modular production. To manage the accumulated effects of dimensional and geometric variability in MiC, Shahtaheri et al. (2017) proposed an approach of combining project risk and structural analysis (risk-based framework) to determine a Pareto-optimal structural assembly configuration with the lowest amalgamated cost of modular production and project risk. This framework is crucial in the planning and design phases of MiC as it allows for an informed tradeoff among modular production cost, transport cost, cost of reworks, and safety of construction workers. Enshassi et al. (2019) proposed a systematic risk management framework to establish proactive management of the persistent geometric variability risks in MiC projects. The proposed framework offers decision support that allows for quantitative

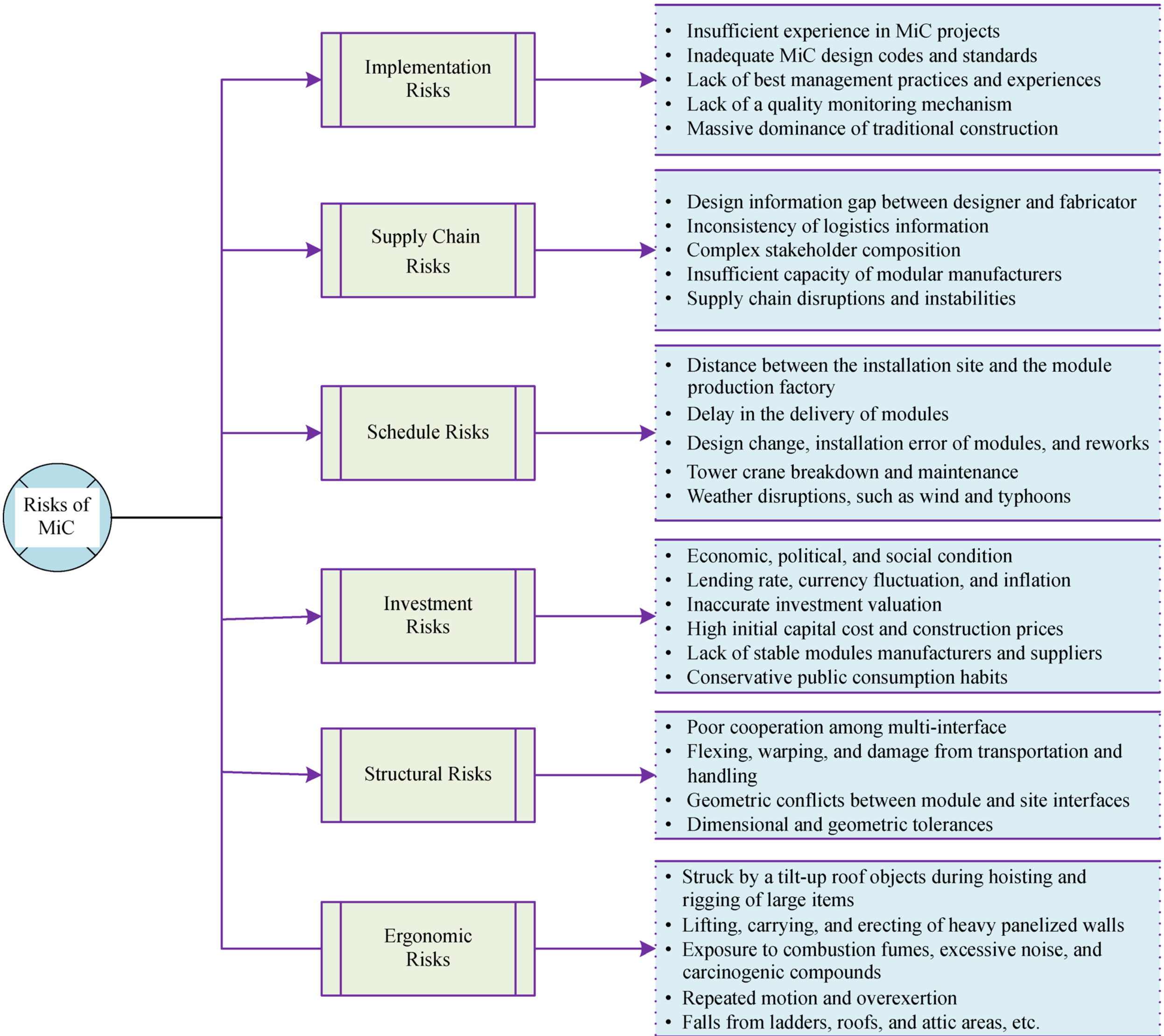


**Fig. 4** Risk breakdown structure of MiC.

evaluation of modularization risks, uses either a strict or relaxed tolerance approach to identify optimum geometric variability, and generates an optimal selection of mitigation strategy based on tolerance theory.

Moreover, some studies investigated the mitigation strategies for ergonomic exposure and safety risks. Li et al. (2019) developed ErgoSystem, an automated post-3D visualization system, which supports a worker-friendly workplace design based on automated ergonomic risk assessment. The system automatically assesses ergonomic exposures and allows for changes to the factory layout for the prevention of ergonomic exposures. Nussbaum et al. (2009) proposed that panelized wall designers should eliminate ergonomic risk by incorporating ergonomic principles into the design of the wall systems. Fard et al. (2017) proposed minimizing injuries by stabilizing structures during lifting, storing, and permanent installation, securing fall protection systems during module installation while working from heights, and developing safety management initiatives in MiC projects.

Studies have also investigated how a lean philosophy can minimize safety risks in MiC projects. Ikuma et al. (2011) implemented Safety and Lean Integrated Kaizen in a modular homebuilding plant and found that back strain, trip hazards, and pinch points were considerably reduced. James et al. (2014) and Nahmens and Ikuma (2009) found that good scheduling practice, housekeeping, systematic workflow, production standardization, and improved handling of materials minimized injuries and improved the safety of construction workers in the manufactured housing industry in the USA. Similarly, Nahmens and Ikuma (2009) implemented lean principles in MiC projects in the USA and observed reduced biomechanical hazards, falls, and low back injuries.

### 4.6 Future research directions

Figure 5 shows the current and proposed future research framework on the risks of MiC. The proposed areas for future research considerations were identified from the gaps in the reviewed studies. The review showed that most of the studies examined MiC supply chain risk events. This finding suggests that risk events in the supply chain constitutes one of the major concerns in MiC. Notably, studies have identified the supply chain risk events (Li et al., 2016; 2017a; 2018a) and the stakeholder-associated risk factors (Li et al., 2016; Luo et al., 2019). However, no quantitative assessment of the supply chain risk events is conducted to identify the most critical ones. It should be reiterated that the MiC supply chain is dominated by multidisciplinary practitioners with disparate objectives and motives (Wuni et al., 2019a). Each stakeholder may focus on the risk associated with a supply chain segment. Thus, aggregation of the risks associated with the entire supply chain of MiC may not serve the specific needs of the disparate stakeholders.

Thus, future studies should identify and allocate risk events in the distinct stages of the supply chain of MiC. Furthermore, limited studies are available on the resilience of the MiC supply chain. However, the adaptive capability of the MiC supply chain, which allows quick recovery following any disturbances, is important (Wang et al., 2018a) to improve the performance of MiC projects. Thus, future studies should develop a risk resilience framework for the MiC supply chain. Moreover, MiC is associated with different risks and uncertainties (Li et al., 2013). However, the magnitude of the risks and uncertainties differs across projects and regions. Given that risk planning is conducted before and during the construction of projects (Baloi and Price, 2003), a risk evaluation index is required as a decision support system to guide the selection (Murtaza et al., 1993) and rating of risks of MiC projects. However, no risk evaluation index and decision support for MiC projects currently exist, which should be developed in future studies.

Furthermore, one significant challenge in the application of MiC is the management of the geometric variabilities during the modular manufacturing and assembly owing to incompatibility between process capabilities and desired levels of tolerance (Enshassi et al., 2019). The prevailing reactive geometric variability management practices continue to apply strict tolerances based on trial and error solutions (Shahtaheri et al., 2017; Enshassi et al., 2019). These practices have proven to be recipes for quality problems, excessive site-fit reworks, cost, and time overruns (Wuni et al., 2019a). Shahtaheri et al. (2017) proposed a geometric and dimensional risk management framework based on strict tolerance approach, whereas Enshassi et al. (2019) proposed a systematic proactive risk management framework and decision support based on relaxed tolerance approach. However, few studies have been conducted regarding the possibility of managing geometric variability risk based on a combined strict–

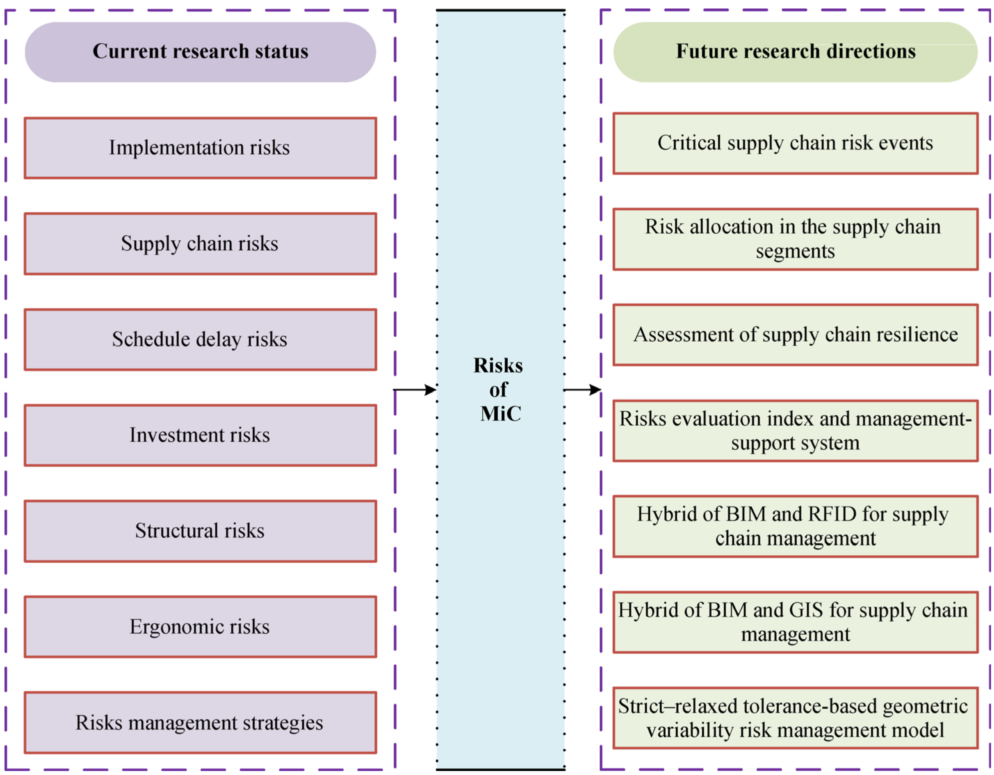


**Fig. 5** Current and future research framework on the risks of MiC.

relaxed tolerance approach. Future studies will conduct a robust assessment of the impact of this combined tolerance-based mitigation strategy on the overall performance of MiC projects.

Finally, studies have deployed smart construction objects and developed RFID-enabled BIM platform, which integrates stakeholders, allowing for the effective monitoring of workflow progress and information/data exchange in the manufacturing, logistics, and on-site assembly stages of the MiC process (Li et al., 2017b; 2018c; Zhong et al., 2017). The Internet of Things (IoT)-enabled BIM platform (Zhong et al., 2017; Li et al., 2018c), smart construction objects, and RFID-enabled smart gateway (Li et al., 2017b) work effectively in ensuring data/information traceability, interoperability, visibility, and exchange; they also support the proactive management of MiC schedule risks (Li et al., 2017b). However, none of the developed platforms incorporated fault-tolerant techniques, which consider the effective elimination of errors caused by faulty operations and inputs. Thus, future studies should modify these platforms to improve their performance.

## 5 Conclusions

This research reviewed and synthesized published literatures that addressed the risks associated with MiC from 1992 to 2019. This study found that research publications on the risk of MiC only witnessed a steady growth within the last decade. This finding suggests that CEM researchers and practitioners are developing increasing interest in understanding the risks associated with MiC projects. Based on a content analysis framework, existing studies are found to have focused mainly on identifying and assessing perceived implementation risks, supply chain risks, schedule risks, investment risks, structural risks, ergonomic risks, and MiC risks management strategies. These multiple forms of risks suggest that MiC is associated with a host of risks and uncertainties. Using the frequency of citation in the published literature, this research identified 19 CREs which have been cited in at least two articles. The 9 most cited CREs include delay in modular delivery, supply chain disruptions and disturbances, inefficient scheduling, design defects and change in project scope, complex stakeholder composition, crane malfunction, insufficient information coordination among project participants, modular installation error, and weather disruptions. These CREs require careful consideration in the implementation of MiC.

Although significant research progress has been made on the risk of MiC, this study identified some areas requiring additional research. Future studies should (i) conduct quantitative assessment and ranking of the CREs in the MiC supply chain, (ii) allocate risks in the distinct stages of supply chain of MiC, (iii) examine the resilience of supply chain of MiC, (iv) develop a risk evaluation index and decision support framework, (v) incorporate fault-tolerant techniques into the integration of RFID and BIM for MiC supply chain management, and (vi) develop a combined strict–relaxed tolerance-based framework for the management of geometric variability risk. This study makes a unique contribution to the scholarly literature on the risk of OSC as it constitutes the first exclusive review on the risks of MiC. It has delineated the boundaries of existing studies, highlighted the gaps and deficiencies in current studies, and proffered some directions for future studies. The research also developed an RBS of MiC and identified some CREs in the implementation of MiC. The CREs contributes to the checklists of risk events associated with OSC and would improve the knowledge of OSC academics, project managers, and industry practitioners regarding the risks associated with MiC. The checklist of CREs may also be useful in risk planning in countries where the MiC market remains in the fledgling stage, and fewer or no bespoke risk assessment exists. For policy-makers, this study highlighted the need for increased commitment to make MiC attractive as the approach continues to fight the historic stigma of prefabricated housing and risk stereotypes. Finally, the proposed research framework provides a useful foundation for future studies. However, this study has the following limitations. First, a sample size of 54 is small. Nonetheless, the current increasing attention paid to MiC renders this review timely and useful. Second, although a comprehensive search was conducted, some relevant articles may have been missed. Thus, the findings of the study should be interpreted against these limitations.

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