Exploring the critical success determinants for supply chain management in modular integrated construction projects

Abstract

Purpose - Modular integrated construction (MiC) projects are co-created by a network of organizations and players providing different roles, information, and activities throughout the supply chains. Hence, effective delivery of MiC projects can hardly be decoupled from effective supply chain management (SCM). This study investigated the critical determinants of effective SCM in MiC projects.

Design/methodology/approach - Comprehensive literature research and expert review identified twenty candidate success determinants, which formed the basis for a structured questionnaire survey of experts in eighteen countries. The study computed the mean scores, normalized mean values, and significance indices of success determinants for SCM in MiC projects.

Findings – The analysis revealed that design for SCM, effective communication and information sharing, organizational readiness and familiarity with MiC, seamless integration and coordination of supply chain, early involvement of critical supply chain stakeholders, and extensive supply chain planning are the top five critical success determinants of effective SCM in MiC projects. The twenty success determinants are categorized into five: project strategy, bespoke competencies, process management, stakeholder management, and risk management.

Originality - The study established a novel set of critical success determinants for SCM in MiC projects that have not been explicitly discussed in the MiC success literature and described their hypothetical dynamic linkages. It contributes to a better understanding of how best to manage the MiC project supply chain effectively.

Research limitations – The study has some limitations. The smaller sample size could affect the generalizability of the results. The generalized analysis of the success determinants overlooked their sensitivities to specific contexts, industry climates, and project types.

Keywords: delivery chain; modular integrated construction; stakeholders; success determinants; supply chain; supply chain management

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Introduction

The last three decades witnessed the renaissance and increased commitment to diffusing modern construction methods in many countries (Hosseini et al., 2018). These innovative construction methods are responses to the intractable problems of the housing crisis, skyrocketing construction costs, rapidly aging construction workforce, staggering productivity syndrome, construction defects, and the increasing requirements to adopt sustainable construction practices (Wuni et al., 2020). Various countries are promoting modern construction methods with different brand names but with similar principles and technical requirements. Modular integrated construction (MiC) is the most advanced form of modular offsite construction where an entire building can be completed in a workshop (Wuni and Shen, 2020a).

The Hong Kong Special Administrative Region government officially launched MiC in 2017 to improve innovation and competitiveness of the local construction industry, respond to the rising need for social housing, realign the industry to cope with the impact of the increasing shortage of skilled labour, and facilitate cost-effective high-density high-rise development in the land-starved city (Pan and Hon, 2018). MiC disrupts the construction ecosystem and defines a relatively bespoke configuration of project supply chains. Effective delivery of MiC projects demands seamless integration and coordination of the interlinked supply chains, including design, procurement, factory production, transportation, storage or buffer, and onsite installation (Hwang et al., 2018). The supply chain of MiC projects also includes a complex network of stakeholders involved in delivering the final product. Hence, there is the requirement to coordinate and manage unique interests, value systems, and objectives of the diverse stakeholders along the different supply chain segments to minimize or avoid adversarial relationships and dysfunctional conflicts (Luo et al., 2019).

MiC projects have specificities, resulting in various structures, configurations, and functions of their supply chain. With rare exceptions, the MiC industry still has temporary supply chains producing one-off construction projects through a repeated reconfiguration of project organization (Vrijhoef and Koskela, 2000). This unique attribute generates instabilities and fragmentation in the MiC supply chain in most countries, especially the interface between the design and construction of MiC projects (ibid). Primarily, the MiC method has a typical make-to-order supply chain (Dawood, 1995), with every project creating a new product or prototype. Aside from minor exceptions, there is little repetition beyond the same project (Vrijhoef and Koskela, 2000).

Typically, a successful MiC project requires coordinating and integrating the often multiple temporary organizations supplying materials, components, and various services throughout the supply chain to ensure seamless flow of information, materials, services, and funds (Aloini et al., 2012). Considering the interdependencies, a disruption in an upstream segment(s) has a negative long-reaching bullwhip effect on the entire supply chain's stability and continuity, especially if the failure emanates from the design stage. Additionally, the supply chain of MiC is incomplete in most economies (e.g., Hong Kong) and usually requires cross-border production and transportation of the MiC modules, with attendants problems of complex custom verification processes and expensive transport costs (Pan and Hon, 2018).

Therefore, a successful MiC project can hardly be decoupled from effective supply chain management (SCM). Yet, there is limited knowledge of how best to effectively manage the MiC project supply chain to guarantee project success. This study aims to examine the critical success determinants for effective SCM in MiC projects. This study differs from Luo et al. (2020), who investigated the supply chain segments and established the limitations of SCM in prefabricated building projects in Hong Kong. It specifically moved beyond the blame cycle to map out relevant strategies for effective SCM in MiC projects. The study's outcomes would have significant practical and theoretical implications. It delineates some critical success determinants of SCM in MiC projects that have not been explicitly discussed in the literature and describes the hypothetical dynamic linkages among the success determinants. The identified success determinants will contribute to the scientific knowledge of the conditions that ensure success in MiC projects. The rest of the paper describes the theoretical and conceptual background, research methodology, results and discussions, contributions of the study, and relevant conclusions.

Theoretical and conceptual background

The supply chain of MiC projects

MiC is an innovative construction approach that leverages manufacturing principles in designing and producing prefinished volumetric modules in an offsite workshop, which are then transported in sections to a construction site for installation in a structure (Wuni and Shen, 2020b). The MiC method significantly adapts and reinvents the typical modular construction approach to integrate advanced production engineering practices, smart digital technologies, and innovative processes (Hong, 2020). Unlike prefabrication and the conventional modular construction technique, where projects can be delivered by assembling 2D or 3D structural building components, the MiC method incorporates prefabricated prefinished volumetric building components (Construction Industry Council, 2019). Indeed, the MiC method was introduced in Hong Kong and Singapore to overcome the engineering limitations of prefabrication and the conventional modular construction for high-rise buildings that accommodate strong wind load from typhoons and resist seismic forces (Hong, 2020). The design, production, transportation, and assembly of the volumetric modules in the MiC method significantly reinvent the supply chain requirements of prefabrication and conventional modular construction (Luo et al., 2020; Yang et al., 2021).

There are significant differences between the processes of traditional construction and the MiC method. For instance, MiC project designs are produced with enhanced manufacturing, logistics, and assembly characteristics. The design for manufacture, logistics, and assembly approach ensures that the detailed design and working drawings of the MiC project lend themselves to modularization, factory production, transportation, storage, and onsite assembly of modules (Building and Construction Authority, 2017). Another significant difference is the requirement for factory production of modules in MiC projects. Unlike traditional projects, there is the requirement to freeze the detailed design early for the manufacturer to produce the modules (Gibb and Isack, 2003).

The MiC supply chain refers to the ecosystem of organizations, stakeholders, information, and resources involved in the interlinked downstream and upstream processes and activities in delivering value in MiC projects (Lönngren et al., 2010). It describes the flow of information and materials throughout the delivery chain, including conceptualization, tendering, design, procurement, construction, hand-over, and construction project use (Vrijhoef and Koskela, 2000). Given the differences between traditional construction and the MiC method, the latter's supply and delivery chain configuration are different from the former. The MiC supply chain stages are usually reified as design, procurement, production, logistics (transportation, buffer, storage), and onsite installation (Luo et al., 2020).

Currently, the local supply chains of most economies are incomplete because the technical expertise, suppliers, or manufacturers and factories can be located overseas, requiring importing foreign expertise or cross-border transportation of modules (Pan and Hon, 2018). In such cases, supply chain volatility or the bullwhip effect may trigger undesirable consequences from demand forecast updating, order batching, price fluctuation, and rationing and shortage gaming (Lönngren et al., 2010). The bullwhip effect is demand volatility that occurs between the tiers of the supply chain (ibid). These configurations increase the supply chain's complexity in some countries, resulting in several pain points, vulnerabilities, disruptions, and risk sources that must be effectively managed to ensure seamless coordination and integration of the supply chains (Luo et al., 2020).

Additionally, there are different networks of stakeholders in the MiC supply chain with their unique goals, value systems, and priorities (Luo et al., 2019). There is the tendency of an ephemeral shifting coalition of the different network of stakeholders from which divergent goals and objectives could emerge, resulting in adversarial relationships and a significant constrain to creativity, innovation, and collaboration throughout the supply chain (Simatupang and Sridharan, 2008). The impact of this temporary shifting coalition could be pronounced if an integrated project delivery method is not employed since it adopts a fragmented approach to construction project delivery dispiriting the integration, coordination, and communication between project partners (Love et al., 1998).

MiC supply chain management (SCM) ensures the seamless integration and coordination of the network of organizations, stakeholders, materials, information, and financial flows throughout the supply chain to create value in the final project for the end-user (Lönngren et al., 2010). It includes the coordination of both onsite and offsite work packages and activities of the different involved stakeholders, adhering to local building codes, meeting quality specifications, and managing the activities of all organizations (e.g., raw material suppliers, suppliers) directly involved in the upstream and downstream flows of materials, services, and information from a source to the client. SCM coordinates and integrates the processes along the delivery chain of MiC projects and establishes a common goal of collaborative working among the involved stakeholders to improve optimization and efficiency in the project delivery process (Aloini et al., 2012).

However, successful SCM in MiC projects is a daunting task. Notably, MiC project supply chains involve a complex network of often multiple temporary stakeholders (e.g., organizations, players), providing various services with potential adversarial relationships. Unlike a typical manufacturing product, the MiC method is both a multi-stakeholder process (e.g., client, owner, designer, contractor, suppliers, consultant) (Luo et al., 2019; Wuni and Shen, 2020c) and an interdependent multi-stage process, including bespoke, one-off conceptualization, planning, design, procurement, factory production, transportation, and onsite assembly for each project. Hence, MiC project SCM must incorporate the interdependencies of the multi-stakeholders and multi-stage processes to coordinate and configure the supply chain to improve transparency and alignment to project objectives and requirements (Yang et al., 2021). Effectively, MiC project supply chains are networks and need to be managed dynamically through ensuring seamless integration and communication across tiers (Luo et al., 2020). Given that a successful MiC project delivery can hardly be decoupled from effective SCM, it is essential to identify, evaluate, and prioritize the success factors for SCM in MiC projects.

Theoretical framework of the success determinants for SCM in MiC projects

Although there are no specific published studies on SCM's success determinants in MiC projects, there is considerable documentation of the success factors for offsite construction projects that could provide a reference to establish a theoretical framework of the success determinants for SCM in MiC projects. This study reviewed the relevant MiC project success literature to establish a theoretical checklist of determinants of successful SCM in MiC projects. For instance, Vrijhoef and Koskela (2000) discussed effective strategies for successful SCM in construction projects, including improving the interfaces between offsite and onsite work packages, seamless integration of the supply chain segments, hedging and buffering, designing for SCM, and long-term partnership of supply chain stakeholders. Luo *et al.* (2020) discussed strategies for effective SCM in prefabricated building projects, including extensive supply chain planning, effective communication among supply chain stakeholders, and effective control of workflows. Masood *et al.* (2021) investigated the supply chain of prefabricated housebuilding from the perspective of small and medium-sized enterprises in New Zealand. They identified determinants of successful SCM, including selecting competent suppliers, seamless integration of supply chains, and collaborative procurement systems.

Lönngren *et al.* (2010) discussed the critical success factors for construction SCM, including effective communication, collaborative procurement systems, long-term partnership, mutual trust among supply chain stakeholders, effective information and communication technology application, and central coordination among the stakeholders employing decentralized task management. Aloini *et al.* (2012) reported the success factors for construction SCM, including effective supply chain risk management, managing complex relationships, fostering trust, effective coordination of materials and information flows, long term partnership, contract management, communication, avoidance of dysfunctional conflicts, selection of competent suppliers, effective use of IT solutions, and early involvement of critical supply chain stakeholders.

Kumar *et al.* (2018) discussed the success determinants of SCM, including customer value orientation, supply chain risk management, and stakeholders' early engagement. Wuni and Shen (2020c) discussed strategies for effective SCM in prefabricated construction projects, including communication and information sharing, extensive supply chain planning, early involvement of critical stakeholders, collaborative procurement system, use of IT solutions, and effective stakeholder conflict resolution. Wuni and Shen (2020a) reviewed the MiC success factors literature. They identified relevant strategies for effective SCM, including designing for SCM, hedging, integrated project delivery methods, IT solutions, communication, extensive planning, coordination of offsite and onsite work packages, and specialist contractor leadership.

The above literature summary indicates that existing studies have implicitly documented success factors relevant to SCM in modern construction methods. A bespoke investigation of the success determinants for SCM in MiC projects is required. SCM's success determinants in MiC projects are scattered and implicitly documented in a wide array of literature. They have neither been reviewed nor explicitly evaluated and prioritized to inform effective SCM in MiC projects. This study used the review as an excellent reference to source and assess SCM's success determinants in MiC projects in this study.

Research methodology and data presentation

The study investigated the success determinants for SCM in MiC projects using a four-stage methodological framework. Stage 1 conducted literature review to identify the research gap and develop a theoretical checklist of SCM success determinants in MiC projects. Stage 2 conducted pilot interviews with MiC experts to validate the identified success determinants and develop a data collection instrument. Stage 3 identified relevant respondents and gathered data on the relative significance of SCM's success determinants in MiC projects. Stage 4 used statistical techniques to pre-test and analyze the dataset to inform conclusions. The methodological framework of the study is described in the following subsections.

Identifying and validating potential success determinants for SCM in MiC projects

The study started with a comprehensive review of relevant articles published in high-quality research outlets to identify potential SCM success determinants in MiC projects. The review established a checklist of twenty-five success determinants for SCM in MiC projects, which were not presented due to space limitations. The study then invited three experts from Hong Kong, Singapore, and Australia with expertise and knowledge of MiC and SCM to review and verify the relevance, representativeness, and practicality of the twenty-five success determinants. The geographic distribution of the consulting experts was informed by the significant advancements these economies have made in the MiC technology and associated SCM. Each expert had at least five years of experience in MiC SCM in their respective economies. The expert review and recommendations confirmed the relevance, usefulness, and suitability of twenty success factors. Table I summarizes the identified and validated success determinants for MiC project SCM, along with the relevant reference. The twenty shortlisted success determinants became candidates for the questionnaire survey.

[**Table I**. Theoretical success determinants for SCM in MiC projects]

Recruitment of relevant respondents

This study employed an expert approach to investigate the success determinants for SCM in MiC projects, instructing the survey of relevant domain experts. In literature research spanning eleven months and industry networking, the study identified the contact details of four hundred relevant domain experts from published articles, workshop reports, conferences, and websites of construction industry councils, institutes, or authorities in different countries. This approach has been used to recruit relevant international domain experts in published studies (Osei-Kyei et al., 2017).

Although the relative significance of the success determinants for SCM is sensitive to different contexts and countries (Wuni and Shen, 2020a), this study employed an international approach to benchmark the key result areas for successful SCM in MiC projects. This study's benchmarking outcome is vital because the supply chain of MiC projects in most countries is incomplete and usually requires cross-border sourcing of materials, expertise, and prefabricated prefinished volumetric modules (Pan and Hon, 2018). Hence, using an international expert knowledge base to evaluate and prioritize the success determinants is desirable. The four hundred experts formed the sample frame of this study.

Data collection instrument design and data collection

Previous studies have predominantly used questionnaires and interviews to investigate SCM's success factors (Aloini et al., 2012; Masood et al., 2021). This study used questionnaires as the primary data collection instruments because it required quantitative opinions of international domain experts to evaluate and prioritize the success determinants for SCM in MiC projects. The structured questionnaire template had two sections. Section one requested the background information of the respondents. Section two requested the relevant domain experts to evaluate the relative significance of the success factors using a five-point Likert scale, comprising 1 (Very insignificant), 2 (Insignificant), 3 (Slightly significant), 4 (Significant), and 5 (Very significant).

The questionnaire was piloted with the three experts who reviewed the list of success factors to identify problematic areas that could compromise the instrument's reliability and validity. All the experts found the questionnaire template appropriate and straightforward. Using the contact details, personalized invitation emails were sent to the four hundred domain experts to confirm their suitability as respondents and complete the questionnaire survey. Following several rounds of weekly reminders, a total of fifty-six valid responses were received in two months. The 56 responses were from 18 countries: United States (10), Canada (8), China (7), Hong Kong (7), Australia (5), Malaysia (4), United Kingdom (4), Brazil (1), Finland (1), Germany (1), Greece (1), Lebanon (1), Singapore (1), Slovakia (1), Spain (1), Sweden (1), Switzerland (1), and Tanzania

(1). The 56 responses were considered adequate for statistical analysis due to some favorable reasons. First, it exceeded the minimum of 30 valid responses required by the central limit theorem for sound conclusions to be made (Ott and Longnecker, 2016). Second, smaller sample sizes have been characteristic of similar published international survey-based studies such as 27 (Sachs et al., 2007) and 47 (Osei-Kyei et al., 2017). Figure 1 shows the profile of the expert panel.

[**Figure 1**. Information about the responding expert panel]

The unequal distribution of experts from academia and industry was expected because the respondents were asked to indicate their main work sector. Academics have closer ties with industry practitioners because they provide research solutions to guide practice and influence policy. Additionally, some academics have substantial industry experience before joining academia. Hence, the unequal distribution does not represent a bias but was strictly coincidental based on the valid responses received. A considerable proportion of the respondents had less than five years of experience, which could be explained by the fact that MiC is relatively new in many countries and fewer practitioners have substantial years of hands-on experiential learning and practical experience of the associated SCM. Figure 1 indicates that most of the expert panel had over five years of relevant work experience in MiC project SCM. Hence, their opinions could have been well-informed by their accumulated wealth of knowledge and experiences. The responses also captured the views of experts from developing and developed economies in the global north and south, lending further credence to the dataset.

Data analysis

The gathered data was coded, managed, and analyzed using the Statistical Package for the Social Sciences (SPSS). The data analysis was completed in two stages. Stage one pre-tested the dataset for reliability, nature of data distribution, and disparity in the responses based on the work sector.

The study used Cronbach's Alpha to measure the internal consistency among the questionnaire's responses and reliability. Although there are various interpretations of the outcomes of the Cronbach's Alpha, the widely accepted interpretations consider a Cronbach's Alpha of 0.70 as the minimum acceptable value (Tavakol and Dennick, 2011). The reliability analysis of the dataset generated a Cronbach's Alpha of 0.889, indicating an excellent internal consistency among the questionnaire's responses.

Additionally, both parametric and non-parametric statistical tests are used to ascertain statistically significant differences among experts' responses. The parametric statistical tests require the data to be normally distributed, whereas the non-parametric statistical tests do not have such requirements (Kim, 2015). Thus, it is acceptable to use the normality test to guide selection of either parametric or non-parametric statistical tests for analyzing the survey-based dataset. The Shapiro-Wilk test is widely used to ascertain whether the dataset is normally distributed (Chou et al., 1998). The decision rule is that the dataset is normally distributed if the success determinants' probability (p) values are less than the chosen level of significance (i.e., 0.05 at a 95% confidence interval). The normality test outcome determines the use of either parametric or non-parametric statistical tests to ascertain whether there are statistically significant differences among the experts' responses based on their work sector. Stage two computed several statistical indicators to prioritize the critical success determinants for SCM in MiC projects. The mean score (μ_i), sample standard deviation (σ_i), and normalized mean value (NMV) of each success determinant for SCM in MiC projects were computed as follows.

$$\text{Mean score } (\mu_i) = \frac{\sum_i^n (X_i * E_i)}{\sum_i^n (E_i)}, (1 \leq \mu_i \leq 5) \quad (1)$$

$$\text{Sample standard deviation } (\sigma_i) = \sqrt{\frac{\sum_i^n (X_i * \mu_i)^2}{n-1}} \quad (2)$$

$$\text{Normalized mean value (NMV)} = \frac{\mu_i - \text{Min.}\mu_i}{Max.\mu_i - Min.\mu_i} \quad (3)$$

$$\text{Significance Index } (S_i) = \frac{\sum_1^5 (X_i * f_i}{5*n} * 100 \quad (5)$$

Where X_i denotes a score given to each success factor, ranging from 1 to 5; E_i represents the rating frequency (1 – 5) for each success determinant; μ_i denotes mean score the of *i*th success determinant; σ_i denotes sample standard deviation of the *i*th success determinant; NMV connotes normalized mean value; S_i represents significance index of the *i*th success determinant; Min.μ_i denotes minimum mean score of the success determinants set; Max.μ_i represents maximum mean score of the success determinants set; and n denotes the sample size.

The mean scores, normalized mean values, and standard deviations played complementary roles in ranking the success determinants for SCM in MiC projects. The latter two indicators were necessary because of the inherent limitations of the arithmetic mean. It is susceptible to outliers, with conflicting interpretations of the minimum critical threshold mean value on the 5-point Likert scale (Ott and Longnecker, 2016). Hence, the normalized mean value, which has a minimum significance threshold index of 0.5, formed the basis for identifying the critical or significant success determinants of SCM success in MiC projects. The significance index also complemented the normalized mean value in determining the significant success determinants. As a thumb rule, a minimum critical threshold significance index of 70% was adopted. As a measure of spread, the standard deviations complemented the mean significance indices in ranking the success determinants. For instance, when two success determinants have the same mean score, the one with the lowest standard deviation is ranked higher. Following these analyses, a conceptual framework is proposed to hypothesize the success determinants for SCM in MiC projects.

Results and Discussions

Frequency distribution of the success determinants for SCM in MiC projects

Table II summarizes the Shapiro – Wilk (S – W) test of normality results. The test was conducted at a 95% confidence interval (i.e., α = 0.05). As shown in Table II, the p-values of the success determinants are less than 0.05, indicating that the data shape is different from a normal distribution (Chou et al., 1998). Thus, it was appropriate to use a non-parametric statistical test to investigate whether there are statistically significant variations among the responses based on their work sector.

[Table II. Frequency of the responses to the success determinants across the rating scale]

The study used the Mann – Whitney (M – W) U test, an ordinal rank-based non-parametric statistical test suitable for comparing two independent groups (Nachar, 2008). The M – W U test was conducted at a 95% confidence interval (i.e., α = 0.05), and the results are shown in Table II. The p-values of the success determinants are greater than 0.05, indicating that none of the success determinants were perceived statistically different by the experts in terms of their work background. Such outcome implies that the expert panel assessments are unanimous and provided a basis to aggregate the responses for statistical analysis (Kim, 2015). The assignment of responses to the success determinants across the Likert scale's different grades is shown in Table II. The results show that the experts mostly rated the success determinants between 'slightly significant' and 'very significant,' pre-empting that the mean scores of success determinants should be situated between 3 and 4 on the 5-point rating scale. Overall, the experts perceived the success determinants as significant to successful SCM in MiC projects.

Critical success determinants for SCM in MiC projects

Table III summarizes the mean scores, significance indices, standard deviations, normalized mean values, and ranks of SCM's success determinants in MiC projects. The standard deviations of the success determinants were between 0.76 and 1.08, indicating minimal dispersion of the responses around the mean scores (Ott and Longnecker, 2016). The assessment results in Table III reveal that nine critical success determinants for SCM in the MiC project, receiving mean scores, significance indices, and normalized mean values greater than 3.50, 70.0%, and 0.50, respectively. The critical success determinants for SCM in MiC projects include a design for SCM (SF1), effective communication and information sharing (SF8), organizational readiness and familiarity with MiC (SF18), seamless integration and coordination of supply chain (SF4), early involvement of critical supply chain stakeholders (SF12), extensive supply chain planning (SF7), effective coordination and management of stakeholders (SF10), improved interfaces between offsite and onsite work packages (SF3), and engaging competent and experienced key players (SF15). Due to space constraints, only the top six critical success determinants for SCM in MiC projects are discussed next.

[**Table III**. Ranking of the success determinants for SCM in MiC projects]

"Design for SCM (SF1)" was ranked the most significant success determinant for SCM in MiC projects and received the highest mean score and significance index of 3.96 and 79.29%, respectively. Design for SCM is a goal-oriented design methodology whereby the project designer explicitly incorporates specific rules, guidelines, and parameters to ensure the project design embodies enhanced SCM characteristics and capabilities (Lee and Sasser, 1995). It recognizes that successful SCM begins with the project design and explicitly designs out supply chain constraints, failure points, risk sources, and vulnerabilities at the design stage (Gokhan et al., 2010). Most of the intractable SCM problems in construction projects are traced to the decisions at the early design phase (Claypool et al., 2014). Thus, the design for SCM adopts an integrated approach to enhance effective SCM. It engages relevant project partners at the design stage to enable the supply chain members to establish a common goal of improving overall performance. Such design rules and guidelines deliver collaborative performance systems (CPS), information sharing, decision synchronization, incentive alignment, and innovative supply chain processes (Simatupang and Sridharan, 2008). Design for SCM has been recognized as a critical determinant of successful SCM in construction projects (Vrijhoef and Koskela, 2000). This finding is consistent with previous studies that concluded that design for procurement, manufacture, logistics and assembly are essential for effective SCM in MiC projects (Tan et al., 2020).

"Effective communication and information sharing (SF8)" were assessed as the second most significant determinant of successful SCM in MiC projects, with a mean score assessment of 3.86 and a significance index of 77.14%. Communication is an indispensable cooperative strategy to get supply chain companies and members to work together to deliver mutual benefits and achieve project objectives (Simatupang and Sridharan, 2008). The supply chains of MiC projects are inhabited by a complex network of organizations and members who co-create and deliver the project (Wuni and Shen, 2020c). Unlike the supply chains of traditional construction projects, the different activities, processes, and stages along the MiC project supply chain are interdependent and dynamic. Decisions made at upstream segments have direct implications on downstream segments. For instance, failure to incorporate manufacturing, transportation, and assembly constraints into the MiC project design would translate into intractable problems in downstream segments. For instance, inaccurate and imprecise specification of allowable tolerances and failure to incorporate the inputs of production engineers in the design are known to generate problematic dimensional and geometric variabilities in the modules (Wuni and Shen, 2020a). For large modules with at least five interfaces with adjoining modules, the onsite assembly of those modules usually requires several step-joints, presenting a significant challenge in dealing with the excessive geometric variability risks in the factory production of modules and onsite assembly (Hong, 2020). The variabilities and inconsistencies embodied in the design translate into geometric conflicts between modules and site interfaces, resulting in less clemency between manufacturing and onsite erection tolerances that usually require expensive additional touch-up works (Building and Construction Authority, 2017). Accordingly, effective communication and information sharing are essential recipes for ensuring collaborative working among independent stakeholders and avoiding problematic disruptions along the supply chain in delivering a project that meets the requirement of client and profitability for all chain members (Lönngren et al., 2010). Previous studies supported this finding that communication and information sharing are potent mechanisms for reducing misunderstandings, managing risks, and speeding workflow along the supply chain (Vrijhoef and Koskela, 2000; Wuni and Shen, 2020a).

"Organizational readiness and familiarity with MiC (SF18)" were ranked as the third most significant determinant of SCM success in MiC projects, with a mean assessment and significance index of 3.80 and 76.07, respectively. Organizational readiness refers to the extent to which the implementing organization(s) or organizational members are technically, psychologically, culturally prepared, and well-equipped to cope with supply chain requirements of the MiC method (Weiner, 2009). MiC is a relatively new business model, and its supply chain configuration is significantly different from traditional projects (Luo et al., 2020). It is a disruptive construction approach to traditional project delivery practices and reconfigures how projects are designed, procured, delivered, and managed. Hence, successful SCM in MiC projects hinges on the main contractor and subcontractors' ability to re-engineer their practices to meet the bespoke SCM requirements of MiC projects. For instance, the implementing organization needs strategies to freeze the design early to allow for a timely workshop production (Gibb and Isack, 2003). The designers need to be prepared to collaborate with the manufacturers at the design stage to proactively design out manufacturing constraints (Wuni and Shen, 2020d). The assembly subcontractor or installers of the main contractor should have experience and be prepared to work with precision and tight tolerances. This finding is consistent with previous studies that emphasized the need for construction organizations to upgrade and upskill in the required production engineering, connection systems, and manufacturing principles (Wuni and Shen, 2020d).

"Seamless integration and coordination of supply chain (SF4)" were assessed fourth most significant determinant of effective SCM in MiC projects with a mean score of 3.79 and a significance index of 75.71%. Unlike traditional construction projects, the supply chains of the MiC project constitute tightly coupled systems because the various supply chain segments are interconnected but fragmented in some economies (Dubois and Gadde, 2002). For instance, Singapore still depends on Malaysian manufacturers for modules to a certain extent (Hwang et al., 2018). Hong Kong also currently relies on factories in Mainland China to produce the modules (Pan and Hon, 2018). Some countries rely entirely on overseas expertise, resources, and supply chains to deliver MiC projects (Wuni and Shen, 2020b). The reliance on overseas factories introduces cross-border logistical challenges with attendant problems of increased cost, stringent custom regulations, and adherence to local building codes (Hwang et al., 2018). Hence, organizational initiatives that leverage digital technology solutions are required to coordinate, integrate, decentralize, and visualize the different stages of the supply chain along with the associated stakeholders. This finding aligns with previous studies that established that MiC companies are increasingly integrating information technology solutions such as internet-of-things, building information modeling, blockchain, smart construction objects, and radio frequency identification systems to seamlessly integrate and coordinate the various stages of the supply chain (Li et al., 2017; Zhong et al., 2017). These approaches provide real-time data-driven supply chain decision support and improve information sharing, collaborative working, monitoring, traceability, and visibility of the supply chain activities (Li et al., 2017).

"Early involvement of critical supply chain stakeholders (SF12)" received the fifth rank, with a mean assessment of 3.77 and a significance index of 75.36%. Through the lens of design for SCM, relevant supply chain partners such as clients, manufacturers, suppliers, main contractor, building authorities, crane specialists, logistics companies, and assembly subcontractors have to work together at the planning and design stages of MiC projects (Building and Construction Authority, 2017). Unlike traditional construction projects, the early involvement of these project partners at the design stage provides the opportunity to leverage their expertise and experience to anticipate, design out, and avoid intractable supply chain problems (Buchanan, 1992). It also allows the critical stakeholders to understand and appreciate early decisions that could influence their roles and responsibilities on the project. For instance, the manufacturing engineers will have the opportunity to understand tolerance specifications at the design stage before they become complicated production challenges when the working drawing hits the production line. This finding is consistent with previous studies that argued that the early involvement of relevant project participants constitutes a practical approach for chain members to define a common goal and work together for mutual benefits (Simatupang and Sridharan, 2008).

"Extensive supply chain planning (SF7)" received the sixth rank, with a mean assessment and significance index of 3.71 and 74.29%, respectively. Supply chain planning is the earliest stage of SCM in MiC projects and reconfigures the supply chain to be consistent with the client's needs or business (Li et al., 2018). It is a proactive approach to identifying the project or business requirements and coordinating the resources, information, services, and processes to deliver optimal value to the MiC project client. Extensive supply chain planning enables the organization to anticipate future project or business requirements, including resources, potential failure points, modules demand, production rate, inventory management, and logistical constraints (Wuni et al., 2019). It usually deploys strategies and methods such as data gathering, lean principles, increased visibility, and standardization (Lee and Sasser, 1995). The planning process enables the organization to reduce or eliminate supply chain waste, failure points, vulnerabilities, and risk sources early before they translate into significant threats to the MiC project realization. This finding is consistent with previous studies that emphasized the role of extensive planning in successful SCM in MiC projects (Li et al., 2018).

Conceptual framework of the success determinants for SCM in MiC projects.

A structural consideration of the twenty success determinants for SCM in MiC projects revealed commonalities. The success determinants can be broadly classified into project strategy, bespoke competencies, process management, stakeholder management, and risk management strategies. Figure 2 shows the groups of success determinants for SCM in MiC projects. The project strategy dimension comprises the implementation of design for SCM rules, the existence of long-term relationships & partnership among project stakeholders, deployment of the collaborative procurement system and contracting (e.g., design-building delivery), early commitment, and continuous support of top management throughout the supply chain, and allocation of adequate funding for the project. Notably, using an integrated project delivery method favors design for SCM because the same entity is responsible for both the project's design and construction functions. The collaborative procurement system can be strengthened by a prevailing long-term working relationship among critical supply chain stakeholders.

The stakeholder management dimension encompasses early involvement of critical stakeholders, communication and information sharing, managing complex potential adversarial relationships and networks, and coordinating the involved stakeholders through information and communication technology solutions. Increasingly, building information modelling is used in MiC projects to foster collaborative working and information sharing among stakeholders (Li et al., 2017).

[**Figure 2**. Conceptual framework of the determinants of success for SCM in MiC projects]

The supply chain risk management dimension of the success determinants includes early planning and managing disruptions, disturbances and failure points; managing the relevant stakeholders to avoid dysfunctional conflicts along the supply chain; developing hedging strategies; and avoiding transport delays, especially when a just-in-time supply chain is not deployed. The competency dimension describes the organizational readiness and bespoke skills required to manage the MiC supply chain effectively. Notably, employing a competent specialist management team, effective leadership of a specialist main contractor, and using competent project participants is essential to reducing waste, redundancies and improving productivity along the supply chain. Finally, three process management success determinants were identified. Extensive supply chain planning, effective coordination of the onsite and offsite workflows, and seamless integration of the supply chains can improve the overall performance of the MiC project.

However, it is noteworhty that the groups of the success determinants in Figure 2 have dynamic relationships. The MiC supply chain is inherently dynamic because of the systemic implication of decisions and processes along the delivery chain, resulting resulting in a closed-loop (Luo et al., 2020). For instance, design for SCM as a project design strategy can minimize the probability of some supply chain risk sources, disruptions, and failure points. Similarly, effective supply chain risk management requires organizational readiness and a specialist management team. Additionally, organizational readiness constitutes a basic recipe for improved management of the processes along the supply chain. Overall, the success determinants for SCM in MiC projects have systemic and dynamic attributes, suggesting the need to adopt a systems-thinking philosophy in MiC project SCM.

Scientific contributions, managerial implications and industry impact

The study's findings have relevant scientific and managerial contributions. Scientifically, the study addressed the existing gap of identifying, assessing, and prioritizing the success determinants for effective SCM in MiC projects. The study's novelty lies in specifically evaluating and ranking the conditions and factors that must be present to ensure successful SCM in MiC projects. Although some of the determinants converge with findings of previous studies, the study identified significant success determinants that have not been explicitly discussed in the literature. These include (i) design for SCM, organizational readiness and familiarity with MiC, (ii) seamless integration and coordination of supply chain, (iii) competent specialist management team, (iv) managing disruptions, disturbances, and failure points, (v) managing complex stakeholder relationships and networks, (vi) effective leadership of a specialist contractor, and (vii) managing and avoiding dysfunctional supply chain conflicts. Hence, the study contributes to how best to successfully manage the MiC supply chain and update the success determinants' theoretical checklist. Additionally, the study grouped and discussed the hypothetical dynamic relationships among the identified success determinants for SCM in MiC projects.

To the practitioners and MiC supply chain managers, some compelling findings have been provided. The study revealed the perceived significance of explicitly designing for SCM in MiC projects and re-emphasized the multifaceted benefits of a collaborative procurement system. Thus, it provides evidence that encourages the adoption of design for excellence methodologies in SCM in MiC projects. The study further corroborated the significance of good communication and information sharing, organizational readiness and familiarity with MiC, seamless integration and coordination of supply chain, early involvement of critical supply chain stakeholders, and extensive supply chain planning to successful SCM in MiC projects. It will inspire management to create enabling environment for these success determinants to thrive in MiC projects. The study also provides new and valuable bespoke information to construction SCM on the relative importance of success determinants, informing supply chain planning and resources allocation for effective SCM in MiC projects.

The study's outcomes also have potential industry impact. A notable challenge of SCM in the construction industry is the persistent issue of insufficient collaboration and information sharing among relevant industry practitioners and stakeholders (Vrijhoef and Koskela, 2000; Wuni and Shen, 2020a). This study revealed the mutual benefits of collaboration and information sharing in MiC projects. Thus, it can inspire the promotion of collaborative modes of procurement system and integrated project delivery methods that encourage the relevant collaboration and information sharing to deliver value-for-money. The study also revealed the necessity of proactive probleme solving in the supply chain and reconsidered the importance of the design stage in SCM. This finding has the potential to encourage front-end and upfront extensive planning and design optimization the construction industry to improve supply chain management. Finally, the study documented the role of organizational readiness on the success of SCM in MiC projects. Thus, it challenges the construction organizations to reconsider their competencies and upskill the relevant industry practitioners when considerin the adoption of MiC and other innovative construction technologies.

Conclusions, contributions, and limitations

Successful MiC project delivery can hardly be decoupled from effective SCM because the client's final value is created by multiple and usually temporary organizations and actors along the supply chain. This study evaluated twenty success determinants for SCM in MiC projects. It leveraged a structured questionnaire survey to gather the opinions of domain experts in eighteen countries on the significance of success determinants. The Shapiro-Wilk test of normality showed that the data was non-normally distributed. Consequently, a non-parametric statistical test known as the Mann-Whitney U test was used to ascertain statistically significant differences among the responses of the two independent groups of experts. The test was conducted at a 95% confidence interval, and results showed that none of the success determinants were perceived statistically different by experts based on their work sector.

Statistical analysis revealed nine critical success determinants for effective SCM in MiC projects. The results indicated that "design for SCM," "effective communication and information sharing," "organizational readiness and familiarity with MiC," "seamless integration and coordination of supply chain," "early involvement of critical supply chain stakeholders," and "extensive supply chain planning" constitute the six most significant success determinants for effective SCM in MiC projects. The twenty success determinants were grouped into project strategy, bespoke competencies, process management, stakeholder management, and risk management. The dynamic attributes of these groups of success determinants were discussed. Despite achieving the aim of the study, some limitations are worth noting. First, the study used a sample of 56 responses, which may affect the generalizability of the results. Second, only experts from Hong Kong, Singapore, and Australia were consulted to verify and validate the practical relevance of the twenty-five success determinants sourced from the literature. While prudent and consistent with existing practices in the literature, the success determinants may be more relevant to these economies. Nevertheless, the factors are linked to standard processes and practices of SCM in MiC projects, which prevail in all countries. Third, the generalized analysis of the success determinants overlooked their sensitivities to specific contexts, industry climates, and project types. As the success determinants were sourced from multiple studies along with expert opinions from eighteen countries, it is likely that the priority list established in this study would be significantly different in any specific context. Fourth, the dynamic attributes of the groups of success determinants were discussed at the conceptual level. The evidences were not derived from data-driven modeling and is open to critique and testing in future research.

Nevertheless, this study still addresses the knowledge gap in identifying the critical success determinants for effective SCM in MiC projects and provides valuable information for MiC organizations to achieve SCM performance requirements and project objectives. This research's most significant contributions include identifying critical success determinants for effective SCM in MiC projects that have not been explicitly discussed in the literature and describing the hypothetical dynamic linkages among the success determinants. Though the identified determinants of success are not exhaustive, the established framework of the success determinants is expected to illuminate further research that will contribute to a more in-depth understanding of MiC SCM. The study also established a valuable register of MiC SCM success determinants and provides a sound basis for future research. Further research should reconsider the relative importance of the identified success determinants in a specific context. It will also be exciting to model the MiC supply chain through discrete event simulation to identify failure points and propose mitigation strategies.

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