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Modeling stakeholder-associated productivity performance risks in modular integrated construction projects of Hong Kong: A social network analysis

Jason Xin ZHOU[1], Lijie HUANG[2], Geoffrey Qiping SHEN[3], Hengqin WU [4*], Lizi LUO[5]

[1]PhD Candidate, Department of Building and Real Estate, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong. Email: jason.zhou@connect.polyu.hk

[2]PhD Student, Department of Building and Real Estate, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong. Email: li-jie.huang@connect.polyu.hk

[3]Chair Professor, Department of Building and Real Estate, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong. Email: geoffrey.shen@polyu.edu.hk

[4]Post Doctorate, Department of Building and Real Estate, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong. Email: hengqin.wu@connect.polyu.hk*

[5]Distinguished Associate Professor, School of Economics and Management, Wuhan University, Wuhan, Hubei Province, China. Email: lizi.luo@whu.edu.cn

*Corresponding Author

Abstract

Modular integrated construction (MiC) has received remarkable attention for enhancing the productivity performance of delivering housing projects in densely populated cities such as Hong Kong. MiC projects suffer from unique risk factors compared with traditional construction methods. Previous studies have mainly focused on the direct linear impacts of risk factors and how they may affect project success. However, the MiC supply chain involves many stakeholders with high interdependency. How the risks are interconnected and interact with different stakeholders is a crucial issue to be analyzed and addressed. This paper deploys a social network analysis (SNA) method to identify and decipher stakeholder-associated productivity performance risks (PPRs) and their interrelations in an MiC project in Hong Kong. Fifteen critical PPRs and twelve essential interactions were demonstrated by simulating the complex network of the target project. Research findings show that inadequate project planning and scheduling has the greatest influence on collaborative decision-making support; Delayed assembly schedule and delayed delivery of modules also exert considerable influence on project planning and scheduling; The main contractor plays a leading role as a coordinator in the whole MiC process. The research further identifies several primary challenges, including the inefficient data capture approach, insufficient supply chain planning and progress monitoring, poor communication and information interchange among project stakeholders, and lack of collaborative decision-making support. This is the first study that dynamically examines and demystifies stakeholder-associated PPRs embedded in MiC projects in Hong Kong on a network basis, which could assist researchers and construction professionals in perceiving, investigating, addressing, and mitigating these risks in an effective and efficient approach.

Keywords: Productivity performance risks (PPRs); Stakeholder interrelations; Social network analysis (SNA); Modular Integrated Construction (MiC)

1 Introduction

The architecture, engineering, and construction (AEC) industry, acting as the largest sector of the world economy, plays an essential role in socioeconomic development (Ofori, 1990). According to the McKinsey report (Barbosa et al., 2017) released in 2017, construction-related spending accounts for 13% of the global GDP, employing 7% of the world's labor. However, the AEC industry has suffered significantly from poor productivity and stagnated innovation compared to other sectors (Bock, 2015). Barbosa et al. (2017) indicated that the construction industry has remained inefficient and exhibits lower productivity, with only 1% annual productivity growth over the past two decades, compared with 2.8% for the total global economy and 3.6% for the manufacturing industry. Traditional technology has reached its potential technological performance limits, making it unable to satisfy the sector's needs for productivity improvements (Bock, 2015) and offering opportunities for developing novel and disruptive solutions for the construction industry. Hong Kong, the world's most densely populated city, has faced increasingly severe challenges due to the shortage of skilled labor, the aging workforce, escalating construction costs, and confined site space (Li et al., 2016, Zhai et al., 2019). Off-site construction, as a solution to these issues, has been widely accepted and performed globally and in Hong Kong due to its advantages, such as improved productivity, shortened project duration, lower project cost, safer and cleaner working environment, and higher final product quality (Lu and Yuan, 2013, Li et al., 2016, Hwang et al., 2018, Shahpari et al., 2020). Gibb (1999) categorizes off-site construction into four types based on the degree of prefabrication: component subassembly, nonvolumetric preassembly, volumetric preassembly, and modular buildings. However, he also argues that there is no clear line for classifying each type.

Modular integrated construction (MiC), as a novel construction method, has progressively attracted considerable attention in industry and academia since its emergence (Zhou et al., 2021). It refers to a transformative construction procedure whereby free-standing volumetric modules (with finishes, fixtures, and fittings) are produced and preassembled in off-site factories and then delivered to the site for assembly (Building Department, 2019, HKCIC, 2019). MiC typically encompasses a higher ratio of prefabricated modules and adopts numerous integrated free-standing modules (Zhai et al., 2019). By shifting most of the on-site construction activities to a controlled off-site factory, MiC provides a considerable enhancement in production quality control (Tam et al., 2007), on-site construction productivity (Shahpari et al., 2020), schedule and cost performance (Hsieh, 1997), and pleasant and safe working environments (Polat, 2008). Generally, MiC projects outperform the traditional construction approach, with improved productivity and performance (Tam et al., 2007, Yang et al., 2019). Productivity is commonly defined as the ratio of output to its associated input (Bröchner and Olofsson, 2012). Construction productivity can be defined as the measurement of outputs achieved through the utilization of various inputs in combination (Yi and Chan, 2014). Shahpari et al. (2020) incorporated time, costs, human force, and management-related factors as critical indicators for assessing productivity. In our research, construction productivity is expressed as an indicator measuring the effectiveness of the construction production process. Risks associated with time, cost, quality, human force, management, organizational, and environmental factors are all determinants for evaluating the productivity performance of an MiC project.

However, the unique and fixed sequence of supply chain processes, such as design, procurement, manufacture, storage, transportation, buffer, and installation, determines the uncertainties and complexities of a MiC project (Wuni and Shen, 2020). Various productivity performance risks (PPRs) exist in MiC projects owing to fragmentation and discontinuity features, such as early design freezing (Choi et al., 2019), schedule delays (Li et al., 2016), high rectification and rework costs (Wuni and Shen, 2020), long lead times (Zhai et al., 2017), transportation restraints (Kamali and Hewage, 2016), installation errors (Li et al., 2016), and poor coordination and collaboration among stakeholders (Zhong et al., 2017). Unlike a conventional project, an MiC project involves multidisciplinary stakeholders. It requires a greater level of information, management, and system integration in the early design stage due to the design freeze feature (Yuan et al., 2021). Meanwhile, different stakeholders dominate their domain in various construction scenarios based on their disparate goals and value systems, exacerbating stakeholder management's complexity in MiC projects (Luo et al., 2019). Thus, stakeholder-associated PPR analysis and management are imperative for successfully delivering an MiC project.

Several previous studies have investigated MiC projects from multifaceted perspectives, such as the opportunities and challenges (Choi et al., 2019), key constraints (Azhar et al., 2013) and major barriers (Wuni and Shen, 2020), critical success factors (Wuni and Shen, 2019), and life cycle performance (Kamali and Hewage, 2016) of MiC projects. Most of these studies, however, are limited to single-perspective research on risk identification and evaluation, which neither considers the interactions among influencing risk factors nor analyzes risks from a dynamic perspective with stakeholders' involvement. In a real-world project, the occurrence of one risk may trigger one or more risks and generate propagating effects, resulting in serial adverse impacts on the entire project (Fang et al., 2012). Perceiving the interrelations of these risks with the consideration of multiple stakeholders is indispensable. Meanwhile, MiC projects are carried out in dynamic, fragmented, iterative, interactive surroundings, whereas the influences of risks cannot be sufficiently identified without analysis on a network basis (Yang et al., 2016). Therefore, to thoroughly investigate and manage PPRs, it is essential to perceive how they interact and mutually affect each other over the whole supply chain process.

Therefore, this study adopts social network analysis (SNA) to examine the stakeholder-associated PPRs and their interactions from a dynamic network perspective. By conducting an in-depth investigation of PPRs with the consideration of relevant stakeholders and dynamic risk interdependencies to address the limitations of conventional static and linear risk analysis. Practically, this paper can provide valuable references for practitioners to manage PPRs in the MiC process more effectively and efficiently. The remainder of this article is structured as follows. In Section **2**, we provide an introduction to the research context and identify related PPRs within MiC. Section **3** delineates the development of the risk management process utilizing SNA. Moving to Section **4**, we consolidate the outcomes of network analysis derived from an actual project. This includes the identification of critical PPRs, major challenges, strategy proposals, and subsequent validation. Section **5** serves as the conclusion, encapsulating our research findings, underlining contributions, and outlining limitations.

2 Research background

2.1 MiC in Hong Kong

MiC is a game-changing, disruptive, groundbreaking method that transforms fragmental cast-in-situ construction into integrated value-driven production and assembly of prefabricated modules (Pan and Hon, 2018). According to HKCIC (2020), the implementation of the MiC method accelerates the completion of housing projects in Hong Kong, with enhanced productivity, shortened project duration, improved working environments and site safety, higher quality, and better project management. These advantages make it exceedingly favorable for high-density cities suffering from housing shortages and crowded site space. Thus, the Hong Kong government endeavors to promote the MiC technique to build more public housing projects (Hong Kong Housing Authority, 2021). The process of MiC projects in Hong Kong comprises five stages: design, manufacturer, cross-border transportation, and on-site installation. Several problems are associated with this abovementioned process. First, early engagement of module designers, manufacturers, and local contractors is needed to meet clients' requirements. Second, mock-ups of each module type are unique to a specific MiC project, which needs to be fabricated and tested before mass production. The inventory will reach zero once the project is completed. No safety stock remains in the factory in a MiC project (Hsu et al., 2018). Thus, if any module is damaged, the reproduction and time costs would be very high compared to those of traditional projects (Valinejadshoubi et al., 2022). Third, special transportation needs to be planned and arranged, especially for large modules. Upon the arrival of modules, the assembly subcontractor will utilize the on-site buffer as a temporary place to store modules. Particular tower cranes need to be set up for precise installation, especially for multiple large modules. As Zhang and Pan (2021) demonstrated, selecting a crane lift and optimal tower crane layout is essential to facilitate safe and efficient module installation in an MiC project. In summary, MiC projects involve multiple practitioners from diverse organizations, resulting in organizational complexity (Choi et al., 2019). Each organization has its own information and management systems with its own predetermined goals engaged in the project (Luo et al., 2019). In addition, traditional data collection and transmission methods still dominate the construction industry. Practitioners may rely on their own isolated systems, which inevitably leads to information inconsistency and cooperation bottlenecks (Zhai et al., 2019). Thus, achieving a seamless and collaborative environment for efficient communication and collaboration is difficult. Since trucks deliver modules from Mainland China to Hong Kong through customs, any deviations in logistics may considerably affect the subsequent assembly process and even the whole project's performance. This situation aggravates the complexity and discontinuity of the whole MiC process.

2.2 PPRs related to MiC

PPRs refer to risks that could adversely affect the efficiency of the whole production process or compromise the project performance by causing schedule delays, cost overruns, lower labor productivity, and poor quality, resulting in delayed delivery of the MiC project. Previous studies have been conducted to identify the inhibitors or stimulators of off-site construction. Mao et al. (2015) surveyed China's significant barriers to off-site construction. The findings revealed that lack of government incentives, high initial costs, and insistence on the conventional construction method are the top three barriers impeding the uptake of off-site construction in China. Taylan et al. (2014) proposed novel hybrid methodologies to assess project risks under incomplete and uncertain conditions. The results showed that the top three risk factors are excessive approval procedures, lack of professional pre-planning studies, and tight project schedules. Azhar et al. (2013) deployed a mixed method to identify the constraints of adopting modular construction. Six major constraints were finally identified. Different regions with different terminologies, such as MiC in Hong Kong, modular building in the UK, and prefabricated prefinished volumetric construction (PPVC) in Singapore, used modular construction as a modern construction method.

Kamali and Hewage (2016) identified the significant challenges of modular construction and showed that project planning, transportation constraints, site restrictions, negative perceptions from the public, high initial costs, and poor coordination and communication are the primary challenges hampering the adoption of modular construction. Hwang et al. (2018) demonstrated five critical constraints for PPVC in Singapore: excessive coordination among stakeholders, additional efforts for project planning and design, ascending transportation needs, early commitment, and higher initial costs. Wuni and Shen (2019) reviewed 30 critical risk factors for MiC projects by examining 39 empirical studies. He also identified the five most essential factors, including the fragmentation and complexity of stakeholder management, higher initial costs, poor supply chain integration and management, delivery delays, and poor government support. Additionally, he proposed insightful strategies to address knowledge, financial, process, and industry barriers to promote the uptake of MiC (Wuni and Shen, 2020). Tsz Wai et al. (2021) argued that MiC should be viewed as a long-term strategy rather than a cheaper short-term option. They prioritized challenges through interviews and surveys and demonstrated road network capacity as the most critical challenge for MiC projects. Yang et al. (2021) proposed a framework to identify sources of uncertainties (SoUs) in off-site logistics of modular construction in high-density cities, identifying 30 key SoUs through case studies and illustrating their influences on cost, time, and quality. Pan et al. (2022) researched the major drivers and constraints to adopting MiC in high-density cities like Hong Kong. They provided 16 strategies to increase the uptake of MiC, highlighting over-stringent regulations, limited codes and standards, limited capable suppliers and contractors, logistics challenges, and loss of saleable areas as critical constraints.

Arshad and Zayed (2022) studied critical influencing factors of the MiC supply chain and employed eigenvector and MICMAC analysis to demonstrate their interrelationships. Results found that assembly-related factors were dominant in affecting the performance of MiC supply chain. However, these studies primarily consider risks or challenges in isolation from a static perspective without considering the interactions between risks. Despite these research efforts, few studies have investigated these risk factors with the consideration of stakeholders and analyzed their interactions. However, these studies can provide a good and formative reference for this study to identify and evaluate PPRs.

Risk identification determines which risk could influence the project's performance. It is an iterative process with the engagement of project participants (Mojtahedi et al., 2010). Numerous techniques are available for identification, including brainstorming, questionnaires, interviews, workshops, cause–effect diagrams, and so forth. A combination of diverse techniques should be more effective for risk identification (Chapman, 2001). Risk assessment aims to measure the influence of the identified risks embedded in a project, provide an overview of the general level and pattern of risk factors, transfer attention to high-priority risks, and offer decision-making support for management's actions (Cooper et al., 2005). The probability that the risk will occur and the corresponding impact level are two essential elements for prioritizing demonstrated risks.

2.3 Importance of Stakeholder Management in MiC Projects

Stakeholder involvement has been deemed indispensable for successfully delivering a construction project (Olander and Landin, 2005). Successful completion of construction projects is based on the proactive cooperation and collaboration of stakeholders to achieve project objectives and expectations over project lifecycles (Atkin and Skitmore, 2008). Yang et al. (2009) stressed that the primary goal of stakeholder management is to develop and manage interrelationships. McElroy and Mills (2000) also showed that project success and productivity improvement can be achieved with the development and management of stakeholder interrelationships. Thus, how stakeholders can influence the productivity performance indicators of projects is crucial and is a fundamental element of stakeholder management in MiC projects.

Previous studies have primarily focused on directly ranking the priority of stakeholders, which assumes a linear relationship between stakeholders and project performance or success (Yang et al., 2011). However, MiC projects are engaged in an intricate, fragmented, interactive, and dynamic environment, where a linear model may not simply evaluate the influence of stakeholders (Luo et al., 2019, Wuni and Shen, 2020, Jiang et al., 2021). In addition, project risks are attributed to various stakeholders with different objectives and concerns in MiC (Wuni and Shen, 2019). Thus, it is crucial to assess the risks from a stakeholder perspective (Yu et al., 2017). This circumstance needs to investigate interrelated and underlying connections between stakeholders and project performance. To bridge this research gap, PPRs are introduced as intermediate variables to elaborate on the impacts of stakeholders on project performance. In this study, project stakeholders are defined as individuals and groups that are actively engaged in the MiC project or whose interests may be affected by project execution or completion (PMI, 2004, Freeman, 2010). Pryke (2004) states that a construction project is a temporary unit network consisting of various stakeholders to achieve a goal together. Thus, SNA is an appropriate approach for investigating network attributes and analyzing their interactions.

3 Methodology

3.1 Research flow of SNA

SNA has been deployed in diverse research domains, incorporating but not limited to project coalition (Pryke, 2004), green building (Yang and Zou, 2014), mega construction projects (Mok et al., 2017), schedule risks (Li et al., 2016), housing demolition projects (Yu et al., 2017), construction safety (Eteifa and El-Adaway, 2018), social sustainability (Wang et al., 2018), transaction costs (Wu et al., 2019), supply chain risks (Luo et al., 2019), and project lifecycle risks (Yuan et al., 2021). Previous studies have indicated that SNA can efficiently investigate stakeholder-associated risks, successful factors, or indicators and their causal relationships. Intending to prioritize stakeholder-associated PPRs, this paper adopts SNA to initiate the PPR network of the whole supply chain of an MiC project in Hong Kong. For a PPR network, the nodes (PPR factors) and links (PPR interactions) are two essential elements that need to be investigated. **Fig. 1** illustrates the classical risk management process (PMI, 2008) and SNA research procedures adopted in this study.

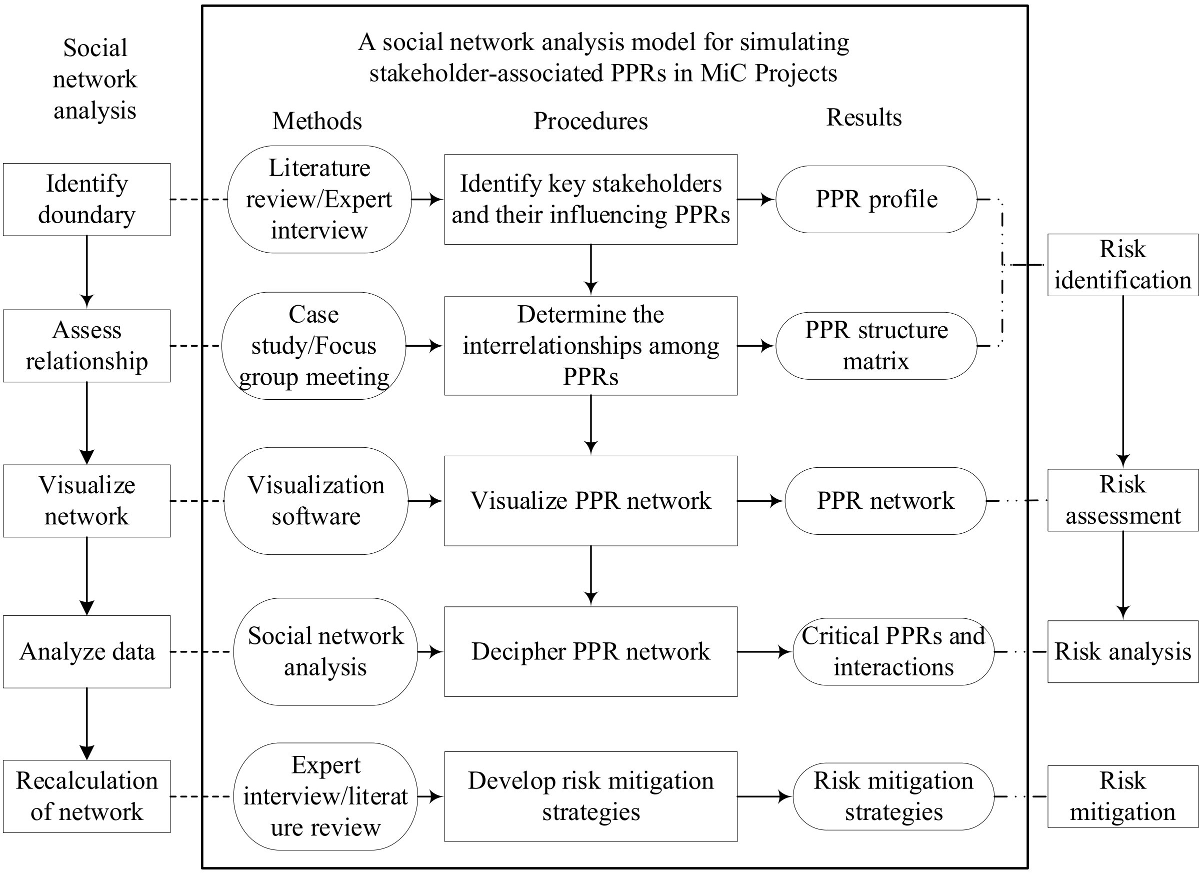

Figure 1 Framework of the SNA-based PPR management method

3.2 Identification of key stakeholders and their PPRs

The chain-referral sampling method used by (Yang and Zou, 2014) was adopted to identify stakeholders involved in the MiC project completely. The selected case study project is a Subsidized Sale Flats Project situated in Tseung Kwan O Area 73A. The main objective of this project is to construct a 33-story residential tower consisting of 330 flats ranging from 1 to 3 bedrooms, totaling 1020 units. Additionally, the project includes the construction of a basement, a 4-level podium featuring commercial shops, car parks, landscape areas, plant rooms, podium gardens, and multifunctional rooms. The Hong Kong Housing Society (HKHS) is the client for this surveyed project. Aggressive Construction Co. Ltd., a well-established construction company in Hong Kong, is leading this project and can provide a comprehensive solution, including design and construction, to their clients. First, the project manager was asked to nominate the closely related stakeholder groups (client, manufacturer, and assembly company); then, these nominees were required to locate others (logistics) that could affect or be affected by the project but who were not incorporated in the chain. A tentative stakeholder group list combined with the literature review (government) was then generated as a complete list of stakeholders in the sampling process. Consequently, seven stakeholder groups were identified in the process, which are numerically denoted S*i*, where *i* = 1 to 7 (S1 = client, S2 = designer, S3 = main contractor, S4 = manufacturer, S5 = logistics, S6 = assembly company, and S7 = government).

Following stakeholder identification, productivity performance risks need to be explored to construct stakeholder-associated PPRs. First, a complete literature review was performed to demonstrate stakeholder-associated PPRs through the whole supply chain process of the MiC project. The literature was searched by two powerful search engines, Scopus and Google Scholar, with publication dates ranging from 1978 to 2022. The keywords used in the literature research included: 'Construction' And '(modular integrated construction OR modular construction OR modular building OR prefabricated prefinished volumetric construction OR prefabrication OR precast construction OR off-site construction OR off-site manufacture OR industrialized construction OR industrialized building)' AND '(risk OR constraint OR challenge OR barrier OR uncertainty).' After conducting a rigorous evaluation of the searched journal papers, 24 pieces of literature were selected to summarize stakeholder-associated risks in the MiC process. Subsequently, a detailed review of the collected documents identified and summarized 30 PPRs in this process. This method has been widely utilized in previous studies to identify critical factors, as Li et al. (2018) and Yuan et al. (2021) demonstrated. Then, in-depth semistructured interviews with selected experts from different stakeholder groups were performed to estimate the comprehensiveness and effectiveness of the identified PPRs. Four experts were then chosen to conduct the interviews. To ensure representativeness and reliability, the designated experts were experienced researchers in MiC projects or directly involved in the target project, at or above the senior managerial level, with at least ten years of experience in their professional domain. The interviewees were invited to discuss the occurrence of the identified PPRs in real-world projects and ensured that these PPRs could potentially influence productivity performance. They also proposed additional PPRs not demonstrated in previous literature reviews grounded in their professions and experiences. **Table 1** summarizes the background information of the interviewed experts.

Table 1 Background information of interviewed experts

No.	Role	Years of work experience in the building construction industry in Hong Kong	Educational background	Position
1	Client	20	Master's degree	Project manager
2	Main contractor	18	Master's degree	Project manager
3	Manufacturer	10	Bachelor of Engineering	Senior engineering manager
4	Academia	12	Doctor of Philosophy	Professor

In the beginning, the researchers provided oral explanations for the surveyed questions by deploying plain language to avoid any ambiguities. Each interview lasted 30 to 45 min, and the interviewees were required to express their opinions based on their practical experience and professional knowledge. The interview questions are as follows. (1) What are the primary risks that may affect the productivity performance of the MiC project? (2) To what extent may these risks influence productivity performance? (3) How do these identified risk factors relate to the corresponding stakeholders? Participants were encouraged to propose additional indicators that were not yet included in the preliminary list. Eventually, a total of 37 PPRs and 60 stakeholder-associated PPRs were compiled based on the literature review and interviews, which are denoted SiPj for further network data processing (where S represents stakeholders, P stands for a PPR, and i and j are the serial numbers). The identified stakeholders and associated PPRs are summarized in **Table 2**.

PPR ID	S. Node	PPR Node	PPR	Category	Reference																								
					0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
S1P1	S1	P1	Insufficient project budgets	Cost		√		√	√	√	√	√	√	√		√	√	√				√		√			√	√	
S1P2 S3P2	S1 S3	P2	Delayed payment	Cost					√			√										√		√					
S1P3	S1	P3	Improper and excessive intervention of clients	Organizational								√			√									√					
S2P4	S2	P4	Incomplete design drawings	Quality	√				√			√											√		√				
S1P5 S2P5 S3P5	S1 S2 S3	P5	Design changes	Cost	√	√				√	√		√		√	√		√		√	√		√	√				√	
S2P6	S2	P6	Design errors	Quality	√										√						√								
S2P7	S2	P7	Insufficient design information transitions	Information interchange	√										√				√		√		√						
S3P8	S3	P8	Inadequate project planning and scheduling	Time	√			√	√	√	√	√						√		√	√		√		√				
S3P9	S3	P9	Lack of a traceable status of modules	Organizational	√		√																						√
S3P10	S3	P10	Inadequate buffer space	Organizational		√	√						√			√	√	√						√			√	√	√
S3P11	S3	P11	Poor management of site layout plan	Organizational	√	√				√	√		√					√	√					√	√			√	√
S3P12 S4P12 S6P12	S3 S4 S6	P12	Insufficient estimation of labor and equipment resources	Organizational				√	√	√		√							√	√	√								
S3P13	S3	P13	Incomplete	Organizati	√		√											√	√		√	√						√	

S4P13 S5P13 S6P13	S4 S5 S6		inspection and handover process	onal																									
S3P14	S3	P14	Incomplete specifications for installation	Quality	√				√	√								√								√			
S3P15 S4P15 S6P15	S3 S4 S6	P15	Lack of a skilled workforce	Quality	√	√				√	√	√	√	√		√	√		√	√				√			√	√	√
S3P16 S6P16	S3 S6	P16	Bad weather conditions	Environment					√	√												√		√	√			√	√
S4P17	S4	P17	Poor quality control of produced modules	Quality				√			√		√			√	√							√	√	√	√	√	
S4P18	S4	P18	Labelled errors	Information interchange	√										√				√										
S4P19	S4	P19	Long lead time of prefabricated modules	Time			√	√		√	√									√				√	√				√
S4P20	S4	P20	Mistakenly delivered modules	Information interchange											√				√										
S4P21	S4	P21	Delayed delivery of modules	Time	√										√				√	√	√		√					√	√
S5P22	S5	P22	Inconsistent information with production and installation	Information interchange	√										√														
S5P23	S5	P23	Transportation restrictions	Safety		√									√		√	√		√		√					√	√	√
S5P24	S5	P24	Prefabricated modules damage	Quality						√					√									√	√				
S5P25	S5	P25	Custom declaration	Organizati										√	√									√	√	√			

				onal																									
S3P26 S6P26	S3 S6	P26	Crane tower breakdown and maintenance	Quality	√										√						√				√				
S6P27	S6	P27	Improper installation sequences	Organizational			√														√							√	
S6P28	S6	P28	Inefficient identification and retrieval of proper modules	Information interchange	√		√								√						√								
S6P29	S6	P29	Installation errors	Quality	√										√				√		√								
S6P30	S6	P30	Delayed assembly schedule	Time	√										√				√		√				√				
S6P31	S6	P31	Rectification of misplaced modules	Quality	√		√			√																			√
S3P32 S4P32 S5P32 S6P32	S3 S4 S5 S6	P32	Inefficient communication and information exchange among project participants	Information interchange	√	√				√		√		√	√		√	√	√	√	√		√	√	√		√		√
S1P33 S2P33 S3P33 S4P33 S5P33 S6P33	S1 S2 S3 S4 S5 S6	P33	Lack of collaborative decision-making support	Information interchange	√			√		√	√	√	√	√		√		√		√	√		√	√	√				
S3P34 S4P34 S5P34 S6P34	S3 S4 S5 S6	P34	Safety accidents	Safety					√													√							√
S7P35	S7	P35	Excessive approval procedures	Organizational						√		√				√										√			

S7P36	S7	P36	Lack of inspirational governmental policies	Environment						√	√		√											√	√			√	
S7P37	S7	P37	Lack of financial incentives	Organizational	√				√	√			√				√								√			√	

Notes: 0= (Interview); 1= (Jaillon and Poon, 2008); 2= (Grau et al., 2009); 3= (Chen et al., 2010); 4= (Nasirzadeh and Nojedehi, 2013); 5= (Azhar et al., 2013); 6= (Zhai et al., 2014); 7= (Taylan et al., 2014); 8= (Rahman, 2014); 9= (Kamali and Hewage, 2016); 10= (Li et al., 2016); 11= (Choi et al., 2019); 12= (Zhang et al., 2018); 13= (Hwang et al., 2018); 14= (Luo et al., 2019); 15= (Wuni and Shen, 2019); 16= (Darko et al., 2020); 17= (Shahpari et al., 2020); 18= (Abdelmageed and Zayed, 2020); 19= (Wuni and Shen, 2020); 20= (Yang et al., 2021); 21= (Jin et al., 2022); 22= (Tsz Wai et al., 2021); 23= (Pan et al., 2022); 24= (Arshad and Zayed, 2022)

Table 2 Summary of identified stakeholder-associated PPRs

3.3 Determination of indicator interrelations

This step aims to determine the links between the nodes (SiPj) and identify the interactions between these identified PPRs. The Design Structure Matrix (DSM) method proposed by Steward (1981) was employed to facilitate the identification process. Links represent relations and dependencies among objects that were identified in Section 3.2. There are three fundamental types of relationships between each pair of indicators existing in the organizational structure: 1) independent indicators refer to indicators that are not related to each other; 2) dependent indicators mean that there is a direct influence between two indicators; and 3) interdependent indicators mean that indicators are involved in a mutually dependent relationship directly or within a larger loop. In this study, the indicator relationship, instead of the individual indicator, is represented by the impact of one indicator over another and the likelihood of the interaction between them.

Subsequently, the research team conducted a focus group meeting to evaluate the interrelationships between these identified PPRs by the same interviewees from the target project. Ten participants were selected from the target project. They are all full-time front-line managers or senior workers with at least five years of work experience from different stakeholder groups. The background information of the selected participants in this step is summarized in **Table 3**. The participants were required to consider all possible interactions based on their practical experience and knowledge. Since the influence can be reciprocal, they also needed to define the direction of the impacts clearly. For example, the impact of S2P3 on S3P4 and the influence of S3P4 on S2P3 are distinctive and regarded as two different links. Participants were asked to answer the following three questions to quantify the influence of one PPR on the other. 1) Does SiPj have an impact on SmPn? 2) If yes, what is the likelihood of this impact? 3) What is the impact level of SiPj on SmPn? Two parameters (likelihood of the occurrence of this impact and level of the impact) are adopted to quantify the influence by using a five-point Likert scale, where “5” indicates the highest level and “1” denotes the lowest level. The overall impact level was calculated by multiplying the two parameters. **Table 4** provides an illustration of the risk structure matrix. For example, if S5P7 has a relatively high likelihood (denoted 4) of affecting S5P8, the impact level is relatively low (denoted 2). This will generate a direct link from S5P7 to S5P8 with an overall influence level of 8. The participants continuously discussed the directions and influence levels of these links until they reached a consensus. The influence level is zero if there is no influence between the two nodes. Ultimately, the PPR structure matrix is established as a fundamental basis for further visualization and analysis of the interaction network.

Table 3 Background information of selected participants

Participant	Stakeholder group	Organization	Position	Working years
1	Client	Hong Kong Housing Society	Project manager	20
2	Client		Senior engineering manager	10
3	Designer	Meinhardt (C&S) Ltd.	Project assistant manager	8
4	Main contractor	Aggressive Construction Co. Ltd.	Project manager	18
5	Main contractor		Project assistant manager	8
6	Manufacturer	Wing Hong Shun Ltd.	Project manager	12
7	Manufacturer		Factory manager	9
8	Logistics	Yingyun Transportation Ltd.	Project assistant manager	7
9	Assembly company	Chuen Kee Ltd.	Site manager	10
10	Assembly company		Assembly foreman	8

Table 4 Illustration of risk structure matrix

	S1P1	S1P2	…	S4P6	S5P7	S5P8	…	S*i*P*j*	…
S1P1									
S1P2	(3,4)			(3,5)					
…									
S4P6		(2,3)			(4,3)				
S5P7	(2,1)					(4,2)			
S5P8				(2,3)					
…									

S*i*P*j*	(likelihood, impact level)
…	

3.4 Visualization of the PPR network

The PPR structure matrix and the nodes and links are imported into NetMiner 4 as the primary input data for constructing the PPR network. Graph G (N, K) is adopted to present the indicator network, where identified stakeholder-associated PPRs are mapped into N nodes linked with K weighted arrows (Fang et al., 2012). Different shapes and colors of the nodes represent different stakeholder groups and indicator categories. At the same time, the thickness of the weighted arrows denotes the overall influence degree (D = likelihood * impact level) between the two PPRs. The connection between S*i*P*j* and S*m*P*n* with an arrow reveals the direction and interactions between the two nodes. The PPR network can disclose the roles and status of stakeholder-associated PPRs in a network by visualizing their interactions.

3.5 Deciphering the PPR network

Two groups of SNA metrics, network-level measures and node/link-level measures, introduced by Yang and Zou (2014), are selected to decipher the PPR network due to their advantages of reflecting the connectedness and complexity of the network and identifying crucial PPRs and their linkages. The network measures incorporate density and cohesion, whereas the node/link measures comprise nodal degree, betweenness centrality, status centrality, brokerage, and ego size. These two metrics are summarized and elaborated in **Table 5**. The analysis results of the PPR network are outlined and discussed in the following section.

Table 5 Description of the SNA metrics for PPR network analysis

Type	Metric	Definition	Description and formula
Network	Density	The proportion of actual linkages in a network to the maximum possible connections if all the nodes are interconnected (Wasserman and Faust, 1994).	$Density(G) = \frac{K}{N(N-1)} = \left(\sum_{S_iP_j,S_kP_l \in G} RSM_{S_iP_j,S_kP_l}\right)/N(N-1)$ *Note: K represents the actual number of linkages, N is the total number of nodes in network G, and S_iP_j and S_kP_l are the interrelated PPRs in risk structure matrix (RSM).* The value of network density varies between zero and one. A higher network density results in greater interactions among stakeholder risks.
	Cohesion	It refers to the network complexity by considering the reachability of nodes, where the number of linkages measures the reachability to approach nodes through the shortest path (Parise, 2007).	$Cohension(G) = \frac{\sum_{S_iP_j,S_kP_l \in G; n \in N} AdjM^z_{S_iP_j,S_kP_l}}{N(N-1)}$ *Note: $AdjM^z$ (adjacency matrix) determines the count of paths with a length of z from one node to another node, where z is calculated based on the average paths between every pair of nodes in the network.* A higher cohesion implies closer risk interactions in the network.
Node	Status centrality	It computes the number of a node's immediate neighbors and all other nodes connected to the focus node through its close neighbors (Katz, 1953).	$StaC_{S_iP_j} = \sum_{d=1}^{\infty} \sum_{S_kP_l \in G; S_iP_j \neq S_kP_l} \alpha^{d-1} (AdjM^d)_{S_iP_j,S_kP_l}$ *Note: The relationship between distant neighbors is influenced by the attenuation coefficient (often α = 0.5). Each connection between two nodes is given a weight (denoted as α^{d-1}), which is determined by α and the distance (d) between the two nodes.* It shows the relative impacts of a node in the network. Central nodes are worthy of more attention.
	Out-degree	It refers to the weighted sum of outgoing links emitted from a node to the immediate neighbors (Loosemore, 1998)	$OutDegree_{S_iP_j} = \sum_{S_kP_l \in G} RSM_{S_iP_j,S_kP_l}$ $InDegree_{S_iP_j} = \sum_{S_kP_l \in G} RSM_{S_kP_l,S_iP_j}$ It shows the impacts exerted by a node on other nodes. A node with a higher out-degree value needs more attention.

	Degree difference	It computes the net influence level by deducting the in-degree value from the out-degree value.	$GapDegree_{S_iP_j} = OutDegree_{S_iP_j} - InDegree_{S_iP_j}$ A node with a higher degree difference denotes a more substantial exerting influence on others than receiving impact
	Ego size	It computes the amounts of direct successors or predecessors of a given node (Everett and Borgatti, 2005).	The ego network density reflects the compact and closeness level of a network.
	Brokerage	It measures the capability of a node to bridge diverse subgroups for a specific partition vector (Gould and Fernandez, 1989).	*Note: Five brokerage configurations include Coordinator, Gatekeeper, Representative, Itinerant, and Liasion.The partitions refer to the different stakeholder groups or risk categories.* The occurrence frequency of each node acting in five brokerage configurations is counted.
	Node betweenness centrality	It refers to the extent to which a node lies between other pairs of nodes based on the definition of the shortest path method (Pryke, 2012).	$Betweenness_{S_iP_j} = \sum_{S_mP_n, S_iP_j, S_kP_l \in G; S_mP_n \neq S_iP_j \neq S_kP_l} \sigma_{S_mP_n, S_kP_l}(S_iP_j)/\sigma_{S_mP_n, S_kP_l}$ *Note: Where $\sigma_{S_mP_n, S_kP_l}$ is the total number of shortest paths that from risk S_mP_n to risk S_iP_j, and $\sigma_{S_mP_n, S_kP_l}$ (S_iP_j) is the number of paths that pass through S_iP_j higher value of betweenness centrality of a node can better control the impacts passing through it.*
Link	Link betweenness centrality	It refers to the extent to which a link lies between other pairs of links based on the definition of the shortest path method (Pryke, 2012).	$Betweenness_{S_iP_j \to S_kP_l} = \sum_{S_oP_p, S_iP_j, S_kP_l, S_mP_n \in G; S_oP_p \neq S_mP_n \neq S_iP_j \neq S_kP_l} \sigma_{S_oP_p, S_mP_n}(S_iP_j, S_kP_l)/\sigma_{S_oP_p, S_mP_n}$ *Note: This equation calculates the betweenness centrality of the link from S_iP_j to S_kP_l.* A higher value of betweenness centrality of a link can better control the interactions passing through it.

4 Results of network analysis

4.1 Results of network-level measures

Graph G (60, 622) is generated to present the PPR network, as shown in **Fig. 2**, which shows that the PPR network comprises 60 nodes linked by 622 weighted arrows. The node colors and shapes represent the PPR and stakeholder categories, respectively. The thickness of the arrows implies the overall influence level for each pair of nodes. Nodes (PPRs) with more linked arrows are located centrally in the network, whereas nodes (PPRs) with fewer connected arrows are placed closer to the network boundary. All nodes are interconnected based on the visual inspection of the network graph, indicating the incredible complexities and intricate cause–effect interrelations during the stakeholder-associated PPR management process. The network density value is equal to 0.176, and the mean geodesic distance between nodes is 2.175 walks. This implies that the network is dense, and the PPRs are close to each other at the macro level. The cohesion value is 0.75, which is larger than the density value. This indicates that the network configuration is more complicated from the aspects of node reachability.

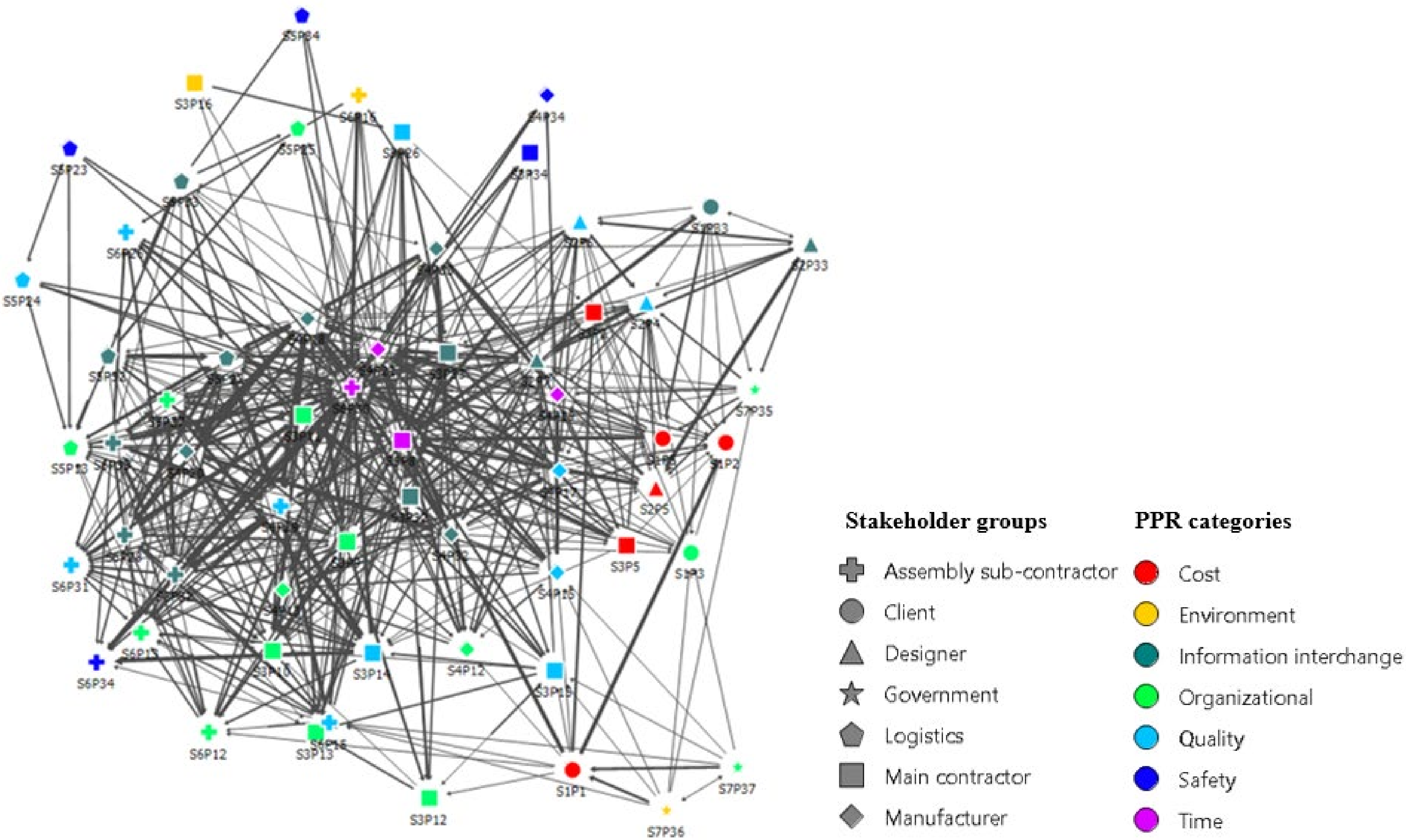

Figure 2 Stakeholder-associated PPR network

4.2 Results of node/link-level measures

4.2.1 Status centrality

Status centrality computes the relative impact of a node by measuring the number of immediate neighbors as well as all other nodes in the network that could be linked to the focus node via its close neighbors (Katz, 1953). Status centrality comprises out-status centrality (outgoing influence) and in-status centrality (receiving influence). Central nodes with higher out-status centrality values require more attention.

Fig. 3 presents the out-status centrality map that depicts the outgoing impact of each stakeholder-associated PPR. The shape and colors represent the stakeholder groups and PPR categories. Some interesting findings can be identified through visual inspection. The nodes located more centrally on the map have a more significant influence on the network interaction. The outbound influences decrease along with the distance between the PPR (node) and the center of the circle. Apparently, the PPRs related to the main contractor, assembly company, and manufacturer are located relatively centrally in the circle, implying that these stakeholders have essential roles and considerable impacts in enhancing the productivity performance of the whole MiC process. The client, designer, and logistic company also have significant roles in MiC projects. This finding differs from previous research (Li et al., 2016, Luo et al., 2019, Yuan et al., 2021), where the client or the government plays a comparatively essential role in the MiC process. Additionally, information interchange, shown in deep green, is situated centrally compared with other PPR categories, revealing that information transfer and sharing play a crucial role in the MiC process. The importance of information interchange-related PPRs in MiC initiates innovative information technologies that substantially improve MiC project productivity. **Table 6** illustrates the top-twelve stakeholder-associated PPRs with high out-status centrality values. S3P9 (lack of a traceable status of modules associated with the main contractor), S3P32, and S4P32 (inefficient communication and information exchange among project participants sourced from the main contractor and manufacturer, respectively) are identified as the top-three PPRs, with high values of 1.812, 1.587, and 1.464, respectively. The top-nine stakeholder-associated PPRs (with a value larger than 1) are primarily related to two risks (P32 and P33) derived from different stakeholder groups, indicating their considerable impacts on the influence level of the entire network. Apart from these two risks, S3P8 (inadequate project planning and scheduling derived from the main contractor), S4P18 (labeled errors), S3P11 (poor management of the site layout plan), S2P7 (insufficient design information transitions sourced from the designer), and S6P29 (installation errors derived from the assembly company) are also considered essential PPRs regarding out-status centrality.

Table 6 Top Stakeholder-associated PPRs with high out-status centrality

Rank	PPR ID	Out-status centrality
1	S3P9	1.812
2	S3P32	1.587
3	S4P32	1.464
4	S6P32	1.428
5	S3P8	1.414
6	S3P33	1.292
7	S4P18	1.241
8	S4P33	1.091
9	S6P33	1.016
10	S3P11	0.988
11	S2P7	0.884
12	S6P29	0.852

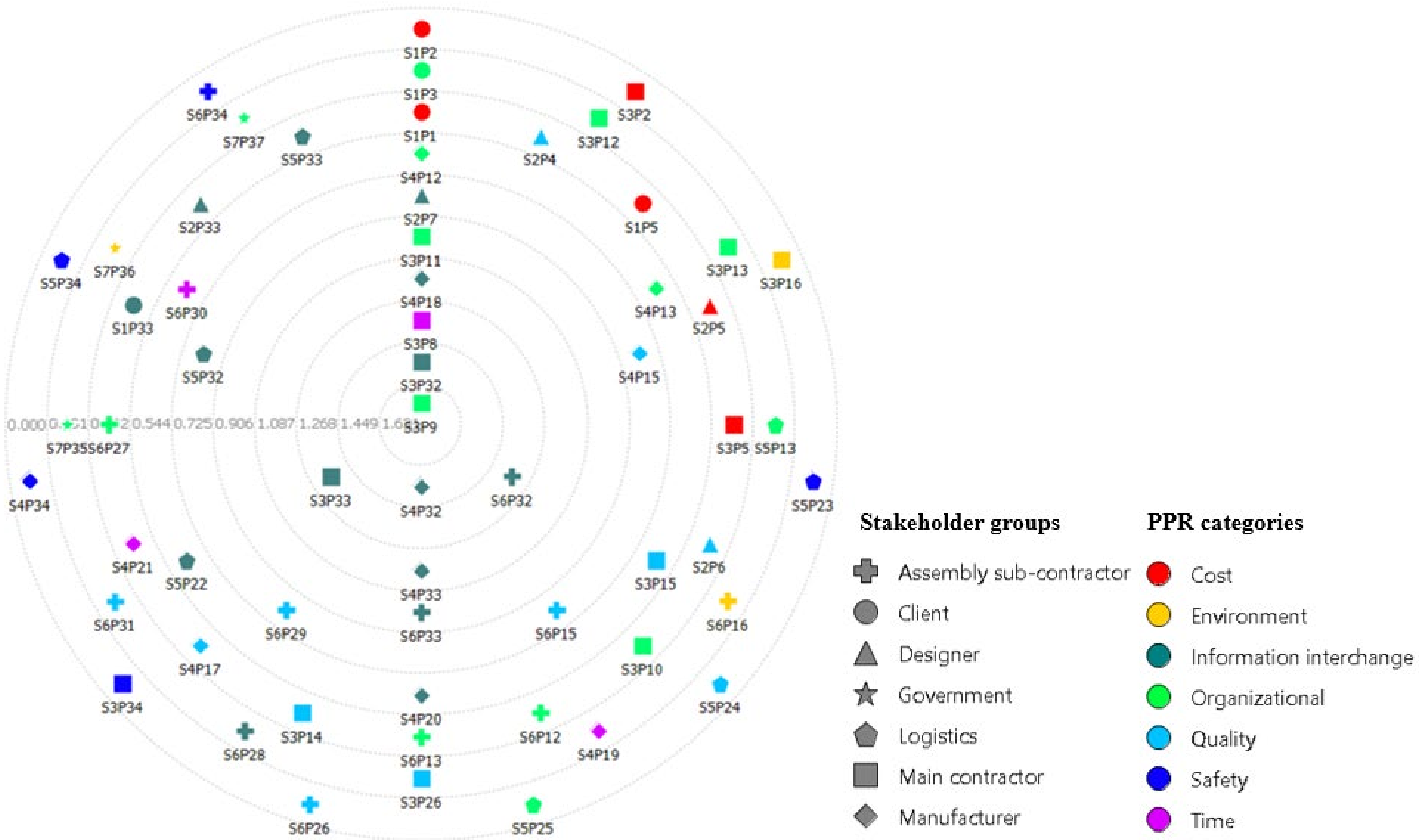

Figure 3 Out-status centrality map

4.2.2 Nodal degree and ego size

Nodal degree, incorporating out-degree and in-degree values, measures the immediate connectivity feature of a node (Loosemore, 1998). The out-degree value shows the direct impact exerted by a node on other nodes, which is computed by the weighted sum of the outgoing links emitted from the node. The in-degree value reflects the direct impact received by a node, calculated by the weighted sum of incoming relations. The degree difference indicates the net impact level calculated by subtracting the in-degree value from the out-degree value. A node with a higher degree difference denotes a more substantial exerting influence on others than receiving impact. The ego network size is another metric that measures the number of direct successors or predecessors of a given node. The ego network density reflects the network compactness and closeness level. A density of 0.3 or above indicates a higher-density network (Everett and Borgatti, 2005).

Table 7 displays the top PPRs based on the out-degree, in-degree, degree difference, and ego size metrics. S3P32, S3P9, and S3P8 are the three most significant PPR factors for the out-degree indicator. In terms of degree difference, S3P32, S3P9, and S3P33 (lack of collaborative decision-making support derived from the main contractor) are the top-three net influence PPRs, demonstrating that they exert considerable direct impacts on other PPRs but receive relatively fewer influences from others. In addition, S4P32 and S6P33 (lack of collaborative decision-making support derived from the assembly company) also have high net influence levels. S6P30 (delayed assembly schedule derived from the assembly company), S3P8, and S4P21 (delayed delivery of modules derived from the manufacturer) are the top-three PPRs with high in-degree values, implying that they are greatly affected by other PPRs in a direct way. These PPRs are all related to schedule issues. Notably, S3P8, S3P11, and S6P30 are particular nodes with high out-degree values of 29, 18 and 13, respectively.

Meanwhile, they are greatly affected by immediate predecessor PPRs, with extremely high in-degree values of 41, 22, and 46, respectively. This indicates that these three nodes are located in a sensitive position of the network and can significantly increase the complexity of the overall network. With the ego network size metric, S6P30, S3P8, and S4P21 are the top-three PPRs that directly affect or are affected by many successors and/or predecessors. As displayed in **Fig. 2,** these three nodes are located in the center of the PPR network. The density values of the listed PPRs are all larger than 0.3, indicating a higher-density network.

Table 7 Top stakeholder-associated PPRs based on nodal degree and ego network size

Rank	PPR ID	Out-degree	PPR ID	In-degree	PPR ID	Degree difference	PPR ID	Ego size	Density
1	S3P32	34	S6P30	46	S3P32	22	S6P30	50	0.317
2	S3P9	30	S3P8	41	S3P9	20	S3P8	47	0.332
3	S3P8	29	S4P21	41	S3P33	18	S4P21	45	0.328
4	S3P33	27	S4P19	23	S4P32	14	S3P32	34	0.472
5	S4P32	24	S3P11	22	S6P33	13	S3P9	33	0.462
6	S6P32	22	S6P29	20	S6P32	11	S3P33	28	0.413
7	S6P33	19	S6P13	20	S4P33	11	S3P11	28	0.415
8	S3P11	18	S6P28	18	S4P15	8	S6P29	27	0.533
9	S4P18	18	S3P2	18	S4P18	7	S4P18	25	0.597
10	S2P7	18	S5P22	17	S5P32	7	S2P7	25	0.540
11	S4P33	16	S6P27	17	S6P15	7	S4P19	25	0.523
12	S5P32	16	S3P10	17	S2P5	7	S4P32	24	0.598

4.2.3 Brokerage

This measures the capability of a node in bridging different subgroups for a specific partition vector (Gould and Fernandez, 1989). In this study, stakeholder categories are selected as the partition vector. Thus, this node measure counts the number of times a particular node acts as five kinds of brokerage configurations (coordinator, gatekeeper, representative, itinerant, and liaison) in linking various stakeholder groups. Nodes with high brokerage values require more attention due to their propagation effects in increasing overall network complexity.

Table 8 presents the top PPRs associated with high brokerage values based on the partition vector as stakeholder groups. These nodes are deemed critical PPRs due to their significant functions connecting different stakeholder groups. Without these PPRs, the influences between stakeholder groups can be eliminated. S3P8, again, is identified as the most crucial PPR based on all types of brokerage roles, implying that it has a significant capability to generate propagating effects and increase overall network complexity. S6P30 and S4P21 are also incorporated in the top-three critical PPRs. All the top PPRs are identified in previously mentioned metrics, indicating their diversified effects on the interactions of the overall network. In addition, three nodes, including S3P33, S3P32 and S4P32, appear in all the above identified top PPRs from diversified perspectives, implying their multiple impacts on other PPRs. Most of the PPRs in the previous tables are associated with the main contractor, indicating that the main contractor plays an essential role in producing propagating effects and increasing the overall network complexity. Additionally, the main contractor, manufacturer, and assembly company are responsible for most of the PPRs in previous tables, demonstrating their important roles in communicating with other stakeholders incorporated in the MiC process.

Table 8 Top stakeholder-associated PPRs based on brokerage values

Rank	PPR ID	Partition value	Coordinator	Gatekeeper	Representative	Itinerant	Liaison	Total
1	S3P8	S3	39	205	179	58	405	886
2	S6P30	S6	20	103	74	25	154	376
3	S4P21	S4	1	18	65	19	139	242
4	S3P11	S3	34	54	81	18	43	230
5	S3P32	S3	34	40	102	5	46	227
6	S3P9	S3	1	43	30	8	84	166
7	S6P29	S6	19	27	52	17	37	152
8	S3P33	S3	13	55	34	0	41	143
9	S4P32	S4	5	27	45	6	28	111
10	S2P7	S2	0	0	43	6	58	107
11	S6P32	S6	10	33	36	5	16	100
12	S4P18	S4	1	9	49	2	32	93

Betweenness centrality

Betweenness centrality refers to the extent to which a node/link lies between other pairs of nodes/links based on the definition of the shortest path method (Freeman, 1979). It signifies the capability of a node or link as a mediator to control the impacts that pass through it (Pryke, 2012). A node/link with a high value of betweenness centrality has excellent power in dominating the influences or interactions passing through it. Mitigating critical nodes or links can reduce the propagating effects of the interactions, thus mitigating the overall network complexity (Freeman, 1979).

Table 9 presents the top-twelve stakeholder-associated PPRs and their interactions with high betweenness centrality. S3P8, with an extremely high node betweenness centrality value of 0.299, acts as a hub connecting multiple pairs of nodes, resulting in propagating consequences in the network. S3P33 and S6P30 are also identified as the top-three critical nodes in the network. By comparing **Table 7** and **Table 9**, three nodes, S6P30, S4P21, and S6P29, are demonstrated to be crucial nodes due to the capability of constructing connections between nodes. Although they do not have strong direct impacts on other PPRs, they play important roles in network connections.

Among all 622 interactions, twelve interrelations are identified as critical links with a high link betweenness centrality greater than 56. Eight out of the twelve critical interactions in **Table 9** are sourced from or targeting S3P8, indicating that it has great power in controlling the influences that pass through it. "S3P8 → S3P33" has the highest link betweenness centrality value of 211.521, indicating that this link has a high capability of controlling the interactions flowing through it. Additionally, all the PPR interrelations are associated with the main contractor, implying that the main contractor plays a crucial role in connecting and communicating with different stakeholders across the whole supply chain process.

Table 9 Top-twelve stakeholder-associated PPRs and interactions based on betweenness centrality

Rank	PPR ID	Node betweenness centrality	Link ID	Link betweenness centrality
1	S3P8	0.299	S3P8 → S3P33	211.521
2	S3P33	0.085	S6P30 → S3P8	102.079
3	S6P30	0.070	S4P21 → S3P8	90.979
4	S3P32	0.068	S3P8 → S4P32	88.773
5	S3P11	0.058	S3P33 → S1P33	79.882
6	S3P9	0.047	S6P29 → S3P9	79.401
7	S4P21	0.044	S3P8 → S3P32	70.134
8	S4P32	0.043	S3P33 → S2P33	69.174
9	S6P29	0.038	S3P11 → S3P32	64.188
10	S6P32	0.028	S3P8 → S5P32	60.544
11	S4P33	0.025	S3P8 → S4P12	57.000
12	S5P32	0.020	S3P8 → S4P18	56.742

4.3 Identification of critical PPRs and challenges

The introduced SNA metrics provide a comprehensive analysis of stakeholder-associated PPRs and their interactions in the case project, including status centrality, nodal degree, ego size, brokerage, and betweenness centrality. The identification process relies on the abovementioned metrics that have been fully investigated and analyzed. Therefore, stakeholder-associated risks with higher status centrality, higher output degree, higher degree difference, larger ego size, higher brokerage values, and higher betweenness centrality should be identified with more attention. However, the rankings of stakeholder-associated PPRs differ in different SNA metrics in the network. Previous studies have frequently selected the top-three or top-five risk indicators in each metric as the critical risks due to their considerable influences on different dimensions in the risk network. Therefore, this study selects the top-three stakeholder-associated risk factors in each ranking list as the critical PPRs. Risks appearing three times or more in each table are also considered essential PPRs, given their multiple functional roles affecting whole-network interactions. Consequently, a total of 15 critical PPRs are determined following the filter criteria. The top-twelve risk interactions identified in link betweenness centrality are deployed as vital PPR interactions. The identified critical nodes are related to eight critical risk interactions, as shown in **Table 10**, reflecting their considerable power in influencing the network complexity. Critical PPRs and interactions are classified into four major challenges, namely, inefficient data capture methods, insufficient supply chain planning and progress monitoring, poor communication and information interchange among project participants, and a lack of collaborative decision-making support. PPR and node interactions in the same category could be addressed with similar strategies. **Table 10** summarizes the critical PPRs and PPR interactions and classifies major challenges.

4.3.1 Inefficient data capture method

Labeled errors (S4P18) and installation errors (S6P29) are two critical nodes reflecting the inefficient data capture method. Traditional labeling and recording methods primarily rely on manual operations and suffer from human errors. Large quantities of project data, such as design data (serial code of modules), production data (production progress), logistics data (delivery date), installation data (location of installed modules), and inspection records, are incorporated in a MiC project. Since offshore MiC projects involve several separate processes, paper-based and hand-operated approaches often cause inaccurate data and information loss. In addition, the impacts of such errors can be consecutive and reversible. For example, labeled errors (S4P18) usually occur in manufacturing owing to the large amounts of prefabricated modules. Since these modules are similar in size and shape and lack a traceable status of modules (S3P9), this may generate mistakenly delivered modules (S4P20) and inconsistent information with production and installation (S5P22), which may affect the downstream assembly stage, causing installation errors (S6P29) and assembly delays (S6P30). Installation errors can produce propagating impacts on the upstream manufacturer stage, can result in delayed delivery of modules (S4P21) and long lead times of prefabricated modules

(S4P19), and can ultimately lead to a revised master program and tight project schedule (S3P8). Moreover, the tight project schedule may cause labeled errors (S4P18) due to human errors because of time constraints.

4.3.2 Insufficient supply chain planning and monitoring

MiC projects often require more customization than traditional prefabrication projects. This can lead to greater variability in the manufacturing process, as well as more complex logistics and supply chain management. The delayed delivery of modules (S4P21) and a delayed assembly schedule (S6P30) are two crucial PPRs in ineffective supply chain planning and monitoring for both upstream and downstream chains in the MiC project. In the MiC supply chain, each working package in each stage is highly related and interactive. For instance, delays in the delivery and assembly stages do not exist independently but interact with each other. Consequently, both delays will lead to tight project schedules or prolonged durations, thus generating propagating effects on the accurate estimation of labor and equipment resources for module production (S4P12). Due to the lack of a traceable status of modules (S3P9), project participants cannot make associated decisions based on the revised schedule for delivery or installation in a timely manner and cannot eliminate the influences caused by schedule delays. Poor management of the site layout plan (S3P11) is another indicator reflecting poor project planning and monitoring. The location of the tower crane and buffer is critical for assembly subcontractors to conduct unloading and erection work. Rational planning and accurate management of the site layout can significantly save secondary handling time and cost, thus improving working efficiency.

4.3.3 Poor communication and information interchange among project participants

Since MiC involves a higher level of integration between different building components and systems, this requires greater coordination and communication among project stakeholders, such as designers, main contractors, manufacturers, logistics, and assembly companies.

Smooth delivery of MiC projects dramatically depends on efficient and timely information interchange and accurate and complete data on related construction activities and objects, such as the status of prefabricated modules, factory or on-site buffer level, and installation rate of each floor. Grounded in in-depth expert interviews, information transmission or interchange of the target project primarily and frequently relies on conventional communication tools, such as email, phone calls, WhatsApp, and paper-based documents. Such obsolete communication approaches impede the working and operation efficiency of the whole supply chain process due to the untimely and incomplete information-sharing mechanism. For example, in a case project, the designer often conveys incomplete and ambiguous design information (S2P7) acquired from the main contractor to the manufacturer due to human errors or unclear paper-based documents. Moreover, due to the design-freezing features of MiC projects, the main contractor cannot convey all the latest information from the designer to the manufacturer. Meanwhile, the manufacturer also cannot respond so quickly to conform to the updated requirements. Consequently, these issues may cause unwanted products, higher costs, and schedule delays. Schedule delays, as a common issue, occur in the entire process of MiC projects and often lead to deviation from the master schedule. The changed master program cannot be delivered to the downstream and upstream stages in an accurate and timely manner due to the lack of rapid and complete information interchange systems among involved parties. Moreover, a frequently changed master program made by the main contractor weakens the information-sharing system among different stakeholders owing to large amounts of changing data and incomplete information. Conversely, poor communication among stakeholders may exacerbate the level of inadequate project planning and scheduling (S3P8). Such an information interchange dilemma among project participants leads to poor communication and information sharing, resulting in low working efficacy and project delay.

4.3.4 Lack of collaborative decision-making support

Critical and imperative events in MiC projects, such as design changes, delivery delays, and schedule revision, require coordination and cooperation from various related stakeholders. Unfortunately, each stakeholder conventionally focuses on his or her own stage with an isolated information system, hampering them from making associated and timely decisions to solve such essential problems. If any unforeseen events happen, such as assembly delay or crane tower breakdown, the corresponding stakeholders cannot be notified immediately. Responsible managers also cannot make quick and appropriate solutions in a dynamic and fragmented working environment based on their own experience. Thus, poor collaborative decision-making support can cause inadequate project planning and scheduling (S3P8). In actual practice, as stated by the interviewees, delayed responses for such critical issues can lead to severe quality and schedule problems, resulting in low productivity, duration, and cost overruns. In addition, as shown in **Table 10**, collaborative decisions made by the main contractor, manufacturer, and assembly company (S3P33, S4P33, and S5P33) have leading influences on the productivity performance of the target project. In addition, as an essential coordinator in the whole supply chain process, the main contractor dramatically influences the client's and designer's decisions.

Table 10 Critical stakeholder-associated PPRs and interactions with summarized major challenges

Critical PPRs/PPR interactions	Associated stakeholder group	Associated risk categories	PPR description	Major challenges
S6P29	Assembly company	Quality	Installation errors due to information inconsistency or workforce carelessness	Inefficient data capture approach: · Labeled and installation errors are primarily caused by human error or ambiguous information. · Paper-based and hand-operated data collection approaches are time-consuming and error-prone. · Tight project schedule may cause labeled errors due to working pressure.
S6P29 → S3P9				
S4P18	Manufacturer	Information interchange	Labeled errors because of human error or ambiguous information	
S3P8 → S4P18				
S6P30	Assembly company	Time	Delayed assembly schedule	Insufficient supply chain planning and progress monitoring: · In adequate project planning, delayed delivery and delayed assembly schedules do not exist independently but interact with each other. · Inefficient progress monitoring due to the lack of a traceable status of modules exacerbates the influences on the productivity performance caused by schedule delays. · Poor site layout management significantly increases the secondary handling time and cost and lowers the working efficiency.
S6P30 → S3P8				
S4P21	Manufacturer	Time	Delayed delivery of modules	
S4P21 → S3P8				
S3P8	Main contractor	Time	Inadequate project planning and scheduling	
S3P8 → S4P12				
S3P9	Main contractor	Organizational	Lack of a traceable status of modules	
S3P11	Main contractor	Organizational	Poor management of the site layout plan	
S3P11 → S3P32				
S2P7	Designer	Information interchange	Insufficient design information transitions to the main contractor and manufacturer	Poor communication and information interchange among project participants:

S3P32	Main contractor	Information interchange	Ineffective communication and information sharing for the main contractor	· Conventional communication instruments hamper the efficient information transmission and interchange among major stakeholders.
S3P8 → S3P32				
S4P32	Manufacturer	Information interchange	Ineffective communication and information sharing for the manufacturer	· manufacturer cannot stay updated with the latest design information from the designer via the main contractor and cannot respond to the changes promptly.
S3P8 → S4P32				
S5P32	Logistics	Information interchange	Ineffective communication and information sharing for the logistics	· Inadequate project planning caused by the frequently revised master program made by the main contractor weakens the information-sharing system among different stakeholders owing to large amounts of altered data and incomplete information.
S3P8 → S5P32				
S6P32	Assembly company	Information interchange	Ineffective communication and information sharing for the assembly company	· Poor communication among stakeholders exacerbates the level of inadequate planning and scheduling.
S6P33	Assembly company	Information interchange	Lack of collaborative decision-making support for the assembly company	Lack of collaborative decision-making support: · Each stakeholder often concentrates on his or her own professional domain with an isolated system, impeding him or her from making associated decisions in time.
S4P33	Manufacturer	Information interchange	Lack of collaborative decision-making support for the manufacturer	
S3P33	Main contractor	Information interchange	Lack of collaborative decision-making support for the main contractor	· Construction senior managers cannot make optimal and appropriate decisions based on their experience in a dynamic and changing working environment.
S3P8 → S3P33				
S3P33 → S1P33				· Delayed responses and suboptimal solutions can cause severe quality and schedule problems, resulting in low productivity, duration, and cost overruns.
S3P33 → S2P33				

4.4 Strategies for addressing the critical challenges

Yu et al. (2017) suggest incorporating expert opinions and literature research into proposed strategies can enhance their effectiveness and efficiency. By drawing on the knowledge and insights of experts in the field and existing research, strategies can be proposed with a more comprehensive understanding of the underlying issues and potential solutions. Based on our previous findings, we conducted an expert interview on how we can mitigate these critical PPRs and address these identified challenges. Interviewees were asked questions based on their practical work experience and professional knowledge. For instance, what strategies can be developed to mitigate the critical influencing PPRs of MiC projects? What advanced technologies can be applied in the MiC project to solve these critical challenges? Five primary strategies were finally identified by summarizing and collating the interviewees' opinions with the literature.

4.4.1 Strategy 1: Digitalize the building components

In the last 20 years, Building Information Modeling (BIM) has become a widespread technology in the construction industry. BIM is a digital representation of the physical and operational information of a building, enabling all stakeholders to generate, manage and share building data throughout its life cycle (Eastman et al., 2011). BIM allows designers to visualize modular buildings in 3D, facilitating the exploration of different design options and identifying potential issues before construction begins, minimizing clashes between different building systems. To achieve a comprehensive overview of the project, the BIM model can be enriched by integrating cost, schedule, sustainability, and other relevant information, forming an nD BIM model. Virtual prototyping (VP) is a computer-based simulation process that involves creating and testing a virtual model of a product, system, or process before its physical construction (Li et al., 2012). This process utilizes 3D computer-aided design (CAD) models and other software tools to simulate, analyze, and test the behavior and performance of the product or system under various conditions and scenarios. Linking VP technology with BIM can enhance the pre-planning and management of the supply chain by simulating and optimizing the key MiC processes, such as design variation, manufacturing planning, and assembly sequence, in a virtual environment before implementation. This allows potential disruptions or critical issues to be identified before they occur, streamlining the MiC process and improving productivity. Furthermore, BIM and virtual prototyping tools can facilitate collaboration and communication among project team members. These tools enable stakeholders to share design models and simulation results, visualize project progress, and identify potential issues.

4.4.2 Strategy 2: Facilitate the adoption of auto-ID techniques

First, automatic identification (auto-ID) techniques such as the QR code, RFID, and NFC can be employed to manage inventory and track modules across the whole MiC phase. An RFID tag can store modular information, such as code, size, weight, etc. QR code can be deployed as a supplementary method to record this information in case of information loss. In addition, project participants can use a mobile device to scan an NFC tag to obtain detailed information about the module. Additionally, integrating auto-ID and GPS technologies can enhance the visibility and traceability of modules such as the vehicle location and delivery route, which can be used to support collaborative decision-making relating to supply chain planning and management. Thus, a smart tag that incorporates RFID, QR code, NFC, and GPS technologies can be developed to enhance the real-time traceability of modules.

4.4.3 Strategy 3: Establish a standardized data capture approach

Creating standardized processes for data capture and ensuring all project stakeholders adhere to these processes can improve data quality and reduce errors. Standardized procedures can include data capture templates, forms, and checklists to capture all necessary data accurately. Regular monitoring and evaluation of data capture processes can help identify areas of improvement and ensure the captured data is accurate and efficient. This can involve reviewing data capture logs, conducting periodic audits, and seeking feedback from project stakeholders on data quality and capture processes. Furthermore, wearable readers are recommended to improve the efficiency of the data connection process. Wearable readers are more portable and convenient in a compact site space than handheld readers.

4.4.4 Develop a digital technology-enabled smart work platform

A smart work platform can be designed to integrate various digital tools such as Building Information Modeling (BIM), virtual prototyping (VP), and automatic identification (auto-ID) technology to enhance the efficiency and accuracy of the MiC process. For instance, the platform can allow designers to develop multifaceted nD models using BIM and simulate different scenarios using VP to identify potential issues before manufacturing occurs. The platform can also facilitate supply chain management by using auto-ID technology to track the movement and status of materials and components, enabling real-time monitoring of inventory and reducing the risk of delays or errors. Furthermore, a centralized system can be established to manage project timelines, schedules, and progress, enabling all stakeholders to monitor the project's status and take necessary actions to meet the project's deadlines. By standardizing the data collection process, the platform can provide a reliable and accurate data repository, which lays a strong foundation for decision-making support. In summary, the collaborative work platform can aid in planning and monitoring project progress, enabling real-time traceability and visibility into the supply chain and providing insights into inventory levels, delivery schedules, assembly sequences, and other critical metrics. The platform can also help identify potential risks or issues and allow for proactive supply chain planning and management.

4.4.5 Extensive use of computing technology

As schedule delays are a common issue in MiC projects, machine learning (ML) and genetic algorithms (GA) are two essential computing techniques that can provide optimal solutions and predictive analytics for MiC projects by utilizing historical data. By optimizing production cycles, supply chain logistics, delivery routes and schedules, inventory management, resource allocation, and project scheduling, machine learning and genetic algorithms can minimize schedule delays and enhance productivity in MiC projects (Mohsen et al., 2022, Wu and Ma, 2022). Genetic algorithms can use predictive models to optimize transportation routes, reduce costs, and increase efficiency (Fang and Ng, 2019). Additionally, machine learning can provide decision support for project managers and stakeholders by predicting project outcomes, identifying risks and opportunities, and recommending strategies to improve project performance. For instance, in the case of assembly delays, a trained model can automatically generate optimal schedules for manufacturing, logistics, and assembly subcontractors to avoid production or delivery queuing. This can help achieve disturbance-free and waste-free resource and task reallocation. By combining machine learning and genetic algorithms, MiC projects can benefit from a powerful suite of tools to enhance productivity. These technologies can analyze large amounts of data and optimize complex processes, improving supply chain management, quality control, maintenance, resource allocation, and decision-making. Overall, leveraging machine learning and genetic algorithms can lead to more efficient and effective MiC projects.

4.5 Network simulation after mitigating critical PPRs and interactions

Table 10 demonstrates the significance of critical PPRs and interactions by employing the SNA metrics. However, the level of their influences on network complexity has not been explored. This section deploys the validation approach adopted by Yang et al. (2016) to simulate and construct a new network after successfully implementing the proposed strategies to verify their impact level on the network. By implementing the proposed strategies, critical nodes and linkages can be eliminated from the original network. Subsequently, during the validation process, the network density, network cohesion, and betweenness centrality are recalculated, effectively reflecting the connectivity and complexity of the entire network. It also serves as a reference tool to validate the proposed strategies' effectiveness and predict the potential reduction of network complexity. The simulation results show that the PPR network is simplified into a graph with 45 nodes and 163 interactions, as displayed in **Fig. 4**. By comparing with the initial network in **Fig. 2**, the network is less dense and complicated by cutting off the links considerably. The network density is reduced by 53.4% from 0.175 to 0.082, whereas the cohesion value decreases by 90.4% from 0.750 to 0.072, indicating a remarkable decrease in network connectivity and complexity. In terms of betweenness centrality, as presented in **Table 11**, node and link betweenness centrality dropped dramatically compared with the original value. In addition, the number of dyadic interactions increases because of the reduced propagation effects, implying that the new network can be easily managed based on simple and straightforward interrelations.

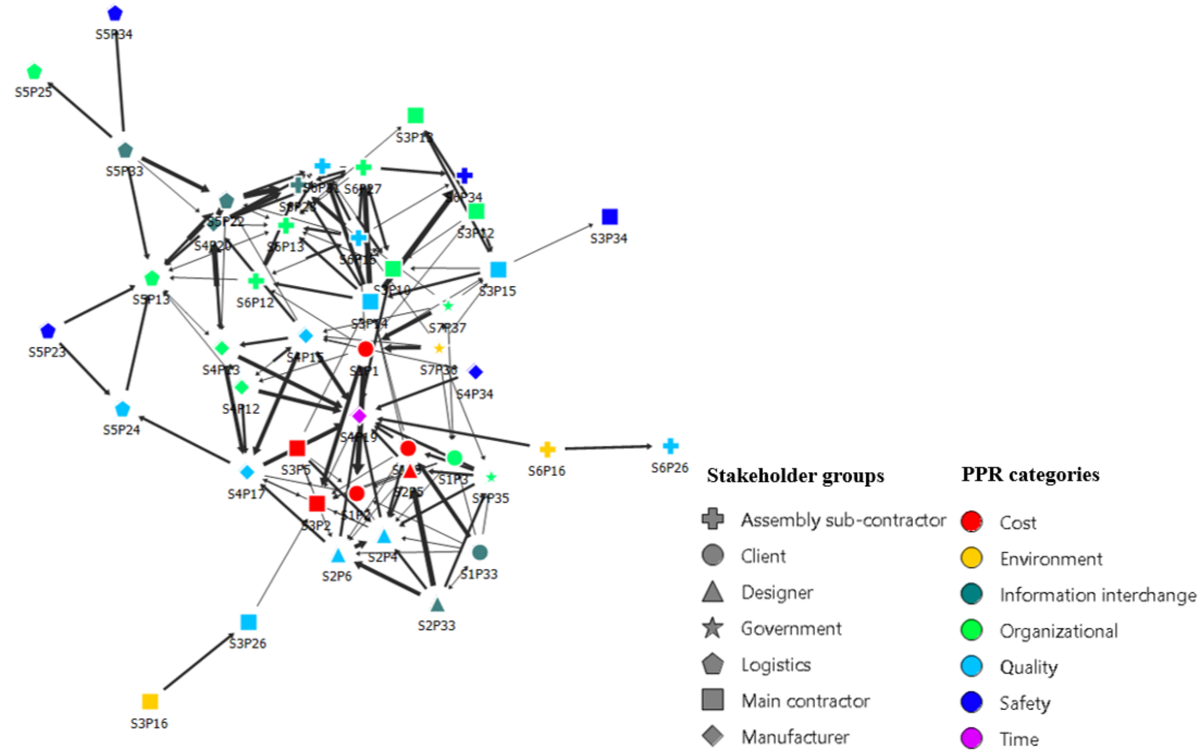

Figure 4 Network simulation after mitigating critical PPRs and interactions

Table 11 Comparison of betweenness centrality after mitigating critical PPRs and interactions

Metric	Node betweenness centrality			Link betweenness centrality		
Rank	Original network	New network	Change (%)	Original network	New network	Change (%)
1	0.299	0.076	74.47	211.521	90.167	57.37
2	0.085	0.054	36.01	102.079	79.543	22.08
3	0.070	0.047	32.96	90.979	63.543	30.16
4	0.068	0.044	34.71	88.773	61.291	30.96
5	0.058	0.042	27.43	79.882	43.067	46.09
6	0.047	0.026	45.85	79.401	36.981	53.42
7	0.044	0.021	52.12	70.134	36.257	48.30
8	0.043	0.018	57.02	69.174	35.643	48.47
9	0.038	0.018	54.09	64.188	33.388	47.98
10	0.028	0.016	40.87	60.544	32.976	45.53
11	0.025	0.014	43.46	57.000	32.729	42.58
12	0.020	0.014	31.71	56.742	32.729	42.32

5 Conclusion

This study deploys mixed methods to identify and demystify the network-based stakeholder-associated PPRs in MiC projects in Hong Kong. Thirty-seven PPRs with seven stakeholders are demonstrated. The SNA method analyzes and prioritizes the PPRs in the target project.

Consequently, fifteen critical PPRs and twelve vital interactions are identified in the analysis model and categorized into four major challenges: an inefficient data capture approach, insufficient supply chain planning and progress monitoring, poor communication and information interchange among project participants, and lack of collaborative decision-making support. The proposed model is further exploited to simulate and verify the influence level of identified critical PPRs and their interactions. Several essential findings from the case study are signified, including 1) obsolete data capture methods are required to be improved to alleviate manual errors; 2) real-time traceable status of modules is imperative for all stakeholders to realize accurate progress monitoring of the supply chain process; 3) the main contractor plays an essential role as a coordinator in the whole MiC process; 4) design change is not incorporated into the critical risks compared to the importance in the conventional prefabrication projects owing to its early design freeze feature; 5) inadequate project planning and scheduling has the greatest influence on collaborative decision-making support, while delayed assembly schedule and delayed delivery of modules exert considerable influence on project planning and scheduling; 6) efficient communication and close collaboration are remarkably important for addressing the fragmented and discontinuous features of the MiC project; 7) the subsequent decision-making support offered by efficient communication and collaboration is essential for the production efficiency of MiC projects; and 8) the five proposed strategies are worthy of in-depth exploration and practical implementation to realize their efficacy fully.

This study provides a theoretically innovative and practically applicable stakeholder-associated PPR analysis model for MiC projects on a network basis. By considering the related stakeholders and dynamic risk interactions, this method can uplift the effectiveness and accuracy of stakeholder-associated risk analysis and management by addressing the drawbacks of conventional linear risk analysis. Understanding the critical challenges embedded in the MiC process and the mechanisms of interrelations between influencing factors can provide value implications to improve the effectiveness, efficiency, and accuracy of PPR monitoring, resulting in the enhancement of productivity performance of the whole MiC project. The SNA model developed in this research is of great value to both researchers and practitioners. By comprehending the complex interrelationships of MiC influencing variables, researchers can expand their understanding of the mechanisms of interactions between these factors, leading to an increase in the number of studies investigating them. Besides, this study can facilitate the development of effective strategies for monitoring and optimizing the MiC process and even the off-site construction industry, ultimately leading to better project performance. Moreover, the identified critical PPRs and linkages, along with the proposed strategies, can be effectively utilized by practitioners to control or even eliminate the influencing factors. This can significantly improve the productivity and efficiency of the entire production process. Furthermore, the proposed strategies are not limited to MiC projects but can also be applied to other forms of off-site construction. This is particularly relevant in densely populated urban areas across the globe, where space limitations and logistical challenges pose significant obstacles to on-site construction. As such, the strategies presented in this study hold considerable promise for enhancing the productivity and efficiency of construction projects beyond just MiC.

Despite these contributions, this research has several limitations. First, the potential risks and risk interactions are proposed and assessed based on the knowledge-based intuition of selected stakeholders. More representatives from different stakeholder groups need to be incorporated into the data collection process to enhance the precision of the PPR interaction assessment. Second, only one MiC project in Hong Kong is investigated and analyzed. To increase the generalizability and representativeness of PPRs in MiC projects, more case studies must be implemented to validate and expand the outcomes of this research worldwide. Third, due to the dynamic feature of the MiC project, the risk network may change over time. Continuous research needs to be executed to periodically monitor and review the risk network with the development of the construction industry.

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