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Understanding Collaboration Requirements for Modular Construction and Their Cascading Failure Impact on Project Performance

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Abstract: Effective implementation of modularization demands close collaboration among the various project stakeholders due to the distinct and complex needs of such construction method. In fact, lack of adequate collaboration is one of the main factors impacting modular construction performance. Despite that, no previous study has yet addressed collaboration requirements in modular construction and their cascading failure impact on project performance. This paper fills such a knowledge gap. To this end, the authors followed a multistep research methodology. First, systematic literature analysis was performed to identify the factors impacting collaboration and the impacted modular risks as well as their cause–effect relationships. Second, two surveys were distributed to collect (1) importance weights and failure probabilities for the collaboration factors; and (2) failure probabilities and performance impacts for the modular risks. Third, network analysis was conducted using in- and out-degree centralities to determine the most influential and sensitive aspects in terms of collaboration. Fourth, independent cascade modeling was performed to capture the cascading failure effect of various collaboration aspects on project performance. Ultimately, a total of 25 factors were found to impact collaboration categorized under four themes, including (1) project organization and control, (2) stakeholders' relationships and characteristics, (3) information sharing, documentation, and technologies, and (4) design and construction planning. Furthermore, 10 modular operation risks were found to be impacted by collaboration in construction projects. Although the most influential factors were related to information sharing, documentation, and technologies, the most sensitive factors fell within the design and construction planning. Most importantly, results show that inadequate collaboration during design and construction planning can lead to 70.6% direct growth in schedule and cost of modularized projects. This paper contributes to the body of knowledge by offering an unprecedented framework that investigates collaboration requirements in modular construction and their interdependencies.

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Introduction

The construction industry started embracing modular construction for its significant short- and long-term prospects, especially after the economic depression (Abdul Nabi and El-adaway 2021; Assaad et al. 2020). Modular construction is characterized by being built off-site in a controlled environment such as a factory, with close control on project inventory, waste, and schedule (MBI 2019). Modular construction is distinct from the conventional stick-built approach in terms of design, engineering, collaboration, logistics, and transportation, among others (Choi et al. 2019; Rahman et al. 2014). Ultimately, planning for modular construction considers multiple aspects, in terms of evaluation of its feasibility as related to the project objectives, configuration of the modules, allocation of work proportion between off-site and onsite facilities, scheduling of lead times, logistics, and interfaces of modules (Smith 2011).

Due to its distinct and complex requirements, modular construction methods demand close collaboration among the various project stakeholders. According to Abdul Nabi and El-adaway (2021), inadequate communication and collaboration is one of the factors hindering the full capitalization on the schedule and cost benefits of modularization in the construction industry. Furthermore, the absence of collaborative planning is regarded as one of the major risks that influence the modularization feasibility and construction performance (Wong et al. 2017; Hamzeh et al. 2017). For instance, a successful implementation of modularization needs extensive coordination and collaboration in establishing a collaborative procurement approach, material inventory management, configuration and constructability of modular design, logistics, and transportation planning (Zhai et al. 2014; Said 2015; Sun et al. 2020; Abdul Nabi and El-adaway 2022). Ultimately, understanding the collaboration requirements and practices in modular construction projects is an essential step toward a more successful implementation and maximal capitalization.

The main goal of collaboration is to ensure information exchange among the various stakeholders (Chen 2010). However, ensuring open communication and information exchange highly depends on the existence of a partnership among the project stakeholders (Zawdie 2012). In fact, although stakeholders' relationships and trust are important, they are rather considered as a prerequisite for a successful collaboration in the project, along with the

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stakeholders' skills and knowledge (Grudinschi et al. 2014). Ultimately, all of the aforementioned aspects further affect collaboration during the design and construction planning process.

For instance, in the law case of Schecter (2018), disputes arose among the project stakeholders due to extra-work claims. The contractor in the law case claimed that its late involvement in the design as well as the resistance of the design team to cooperate and coordinate, led to many design errors, changes, and onside conflicts. Thus, inefficient collaboration has a propagative effect where the failure in one collaboration aspect can lead to cascading impact on other aspects and subsequently project implementation. Ultimately, achieving adequate collaboration and coordination is influenced by various interdependent project aspects and decisions that should be addressed during the early phases of construction projects. Therefore, to ensure better understanding of collaboration requirements in modular construction projects, there is a dire need to consider not only the various influential aspects but also their interdependence or cause–effect relationships.

Knowledge Gap, Goal, and Objectives

As indicated in Table 1, various research studies have investigated different collaboration aspects related to modular construction methods. For instance, some studies focused on integrating advanced visualization techniques and technologies including virtual reality (VR) and augmented reality (AR) to promote information sharing during either construction or design planning (Han et al. 2017, 2015; Rahimian et al. 2019; Ezzeddine and de Soto 2021; Lee and Lee 2021). On the other hand, some studies focused more on the organizational related aspects of collaboration as well as stakeholders' relationships, including the work of Shafiee et al. (2020), Dowsett et al. (2019), and Hofman et al. (2009).

Ultimately, the existing literature falls short in (1) addressing all the different aspects affecting collaboration in modular construction projects including those related to project organization, information sharing, construction planning, and design planning, (2) identify the modular construction operations requiring efficient collaboration among project stakeholders, and (3) investigate the cascading effect of the failure of the different collaboration aspects on each other as well as on project performance.

As such, the goal of this paper is to understand collaboration requirements in modular construction projects and their cascading failure impact on project performance. To achieve that, the objectives of the authors are to (1) identify the set of factors affecting collaboration as well as another set of factors of modular risks requiring high level of collaboration, (2) determine the most influential and sensitive factors in relation to collaboration, and (3) study the cascading failure effects of different collaboration aspects and their impact on modular performance.

Background Information

In this section, the authors provide background information about the current strategies used for collaboration in modular construction in different phases of construction projects as well as the different research methods employed in this study including reasons for their selection.

Collaboration Strategies in Modular Construction

Collaboration strategies are critical in modular construction because it involves coordination among various stakeholders, including designers, contractors, suppliers, and manufacturers. For instance, effective organization is essential in modular construction because it can improve communication, reduce conflicts, and

Table 1. Summary of relevant studies

References	Scope	Collaboration aspect	Impact on performance
Han et al. (2017, 2015)	Three-dimensional-based planning and selection of cranes	Information sharing and construction planning	No
Rahimian et al. (2019)	Integration of virtual and virtual reality to building information modeling	Information sharing and design planning	No
Ezzeddine and de Soto (2021)	Use of game engine technologies to connect modular team	Information sharing	No
Shafiee et al. (2020)	Comparison of different incorporation strategies of modularization	Organization	No
Dowsett et al. (2019)	Road map for modular construction supply chain integration	Organization	No
Lee and Lee (2021)	Incorporation digital twin for better coordination of supply chain in modular construction	Information sharing	No
Hofman et al. (2009)	Establishing supply chain network for modular products	Organization and stakeholders' relationships	No
Pablo and London (2020)	Developing models of collaboration for off-site construction methods	Organizational	No
Ramaji and Memari (2018)	Comparison of various information standards for modular construction projects	Information sharing and interoperability	No
Mossman and Serhan (2021)	Investigating synchronization between off-site and onsite activities of modularization	Construction planning	No

enhance project outcomes. One of the main current organizational strategies is vertical integration, which involves central coordination and maintaining long-lasting relationships with supply chain partners (Eldamnhoury and Hanna 2020). Vertical integration strategies can involve mobilizing subcontractors, designers, and manufacturers to deliver complete projects, or engaging in strategic collaborations with partners (Vrijhoef 2011; Sheffer 2011). Intrinsic organizational fragmentation is a key element making modular interface management difficult (Zhang et al. 2022). Primary modular construction issues arise from managerial factors related to the organizational aspect (Pan et al. 2023). Thus, management aspects such as planning and communication at the organizational level should be enhanced for modular construction projects.

Although lean construction intends to enhance collaboration and construction planning by reducing waste and accelerating the construction cycle, simulation techniques have been also presented as a strategy to enhance construction planning in modular construction (Bhatia et al. 2022; Zhang et al. 2020). Another effective strategy is early involvement of subject matter experts and module specialists in the construction planning stage and hiring experienced craft professionals and managers while offering appropriate training (Pan et al. 2023). Other collaboration strategies like global positioning systems (GPS), building information modeling (BIM), and radio frequency identification devices (RFID) are technologically mature and ready to use, but industry standards tailored to modular construction are needed to facilitate their adoption (Wang et al. 2020).

The use of BIM as a digital tool helps to improve the effectiveness of information sharing, which in turn reduces the amount of unnecessary data and assists in the optimization of VMC building design (Khan et al. 2023). As a result, this reduces the creation of waste and the consumption of resources. The accuracy of information sharing in modular construction can be compromised due to the use of paper or paint labels, the fragmented nature of construction organizations, and a lack of assurance mechanisms to check for updated information (Wu et al. 2022). Current information sharing strategies for modular construction still need to obtain rapid approval and solve the security issues (Li et al. 2022). Therefore, it is important to establish a unified information sharing platform and assurance mechanisms to ensure the accuracy and completeness of information sharing in modular construction.

The aforementioned project phases incorporated various current strategies for collaboration in modular construction, such as BIM-based design and construction coordination, off-site construction planning, modular design for manufacturing and assembly, and modularization team structure. They also highlight the benefits of these strategies, including improved project performance, reduced construction time, improved quality, and enhanced communication and collaboration between stakeholders. However, there are still gaps in the literature, such as the need for standardized protocols and guidelines for such collaboration and the need for further research on the effectiveness of these strategies in different contexts such as large-scale projects, complex designs, and different geographic regions. Additionally, the integration of these strategies with emerging technologies such as artificial intelligence (AI) and the Internet of Things (IoT) can be further explored to enhance their effectiveness in modular construction.

Network Theory

To achieve the objective of this paper, there is a need for a methodological approach that efficiently captures the cause–effect relationships between the various factors impact collaboration in modular construction projects. In relation to that, network theory–which is a part of graph theory–is considered an appropriate approach because it provides an effective way to analyze dependency between system elements and investigate their cause–effect relationships (Yang and Zou 2014). Ultimately, network theory is suitable for systems consisting of complex relational structures where (1) their individual elements can either have impact or be impacted by other elements within the system; and (2) the interdependence among the various elements have an impact on the system performance (Fang et al. 2012; Dogan et al. 2015; Mok et al. 2017; Chen et al. 2020).

For the scope of this paper, the level of collaboration in construction projects depends on a set of interdependent that can have impact each other within the system (cause–effect relationship). Furthermore, as mentioned previously, any failure in one of the collaboration factors may propagate to other factors, leading to poor collaboration levels and subsequently triggering various modular risk events impacting the performance of the project. Thus, based on the aforementioned, the authors adopted network theory to represent the set of factors impacting collaboration and their cause–effect relationships.

Network theory represents any system as nodes and edges, where the nodes represent the system elements and the edges represent the relationship among them (Wasserman and Faust 1994). Most of the applications of network analysis were related to research work investigating social structures and networks (Moreno 1960; Pow et al. 2012; Lee et al. 2017). However, graph theory and network analysis possess many benefits that allow the examination of elements importance (factors) in a system based on their interconnectivities and the cause–effect relationships associated with them (Abdul Nabi and El-adaway 2022). In other words, following such an approach will allow the assessment of system elements based on centrality measures reflecting their interconnectivity with—as well as dependency and influence on—other factors in the network (Waltman et al. 2010).

Although it was commonly applied to social sciences, network analysis has been gaining great attention by researchers in the construction field to investigate interdependency among various project factors or aspects including, but not limited to (1) causes of fatalities (Eteifa and El-adaway 2018), (2) causes of disputes (Abdul Nabi and El-adaway 2022), (3) schedule risk of infrastructure projects (Chen et al. 2020), and (4) transportation flow (El-adaway et al. 2017). However, none of the previous studies have addressed the aspects that affect collaboration in an interdependent manner neither in relation to construction industry in general nor to modular construction in particular.

Cascade Modeling

There are several methods that could be used to understand failure propagation across complex systems, including agent-based modeling (Rahmandad and Sterman 2008), cellular automata (Bak et al. 1987), epidemic models or susceptible-infected-recovered (SIR) models (Wu et al. 2018), independent cascade model (ICM), or linear threshold models (LTM) (Jin et al. 2016). Cascade modeling techniques in social complex networks identify the most important nodes that can spread information to the remaining nodes in the network (Wang et al. 2013).

However, these techniques were also adopted in other nonsocial-related fields. For instance, Jin et al. (2016) used the ICM and LTM techniques to model financial risk propagation across the various stock markets represented as system of nodes and edges. Su et al. (2021) analyzed risk propagation in integrated project delivery method (IPD) construction projects using epidemic or SIR models. Zhao et al. (2018) adopted SIR models to model credit risk diffusion in supply chain finance network. In addition, Liu et al. (2019) used a threshold model to study workplace hazards following a cascade failure approach. For the scope of this paper, the network consist of collaboration factors rather than individuals or agents. Thus, and to achieve the third objective of this study, the literature supports the use of SIR models, ICM, or LTM rather than agent-based modeling or cellular automata as the failure of collaboration factors, and the associated propagation resemble that of the risk propagation mechanism modeled by the previously mentioned studies (Zhao et al. 2018; Su et al. 2021).

ICM, SIR, and LTM are all probabilistic-based cascading techniques with slightly different assumptions in the propagation mechanisms. For instance, ICM is considered a generalized form of the SIR model. However, instead of assuming a single propagation probability for all edges in the network (SIR model), ICM assumes that each edge has a distinct probability of infection or propagation (Shakarian et al. 2015). Because SIR models are used for simulating infections during epidemics, the infection probability can be assumed to be constant (El Moustaid et al. 2019). However, for the analysis of this paper, the collaboration factors may have distinct importance and thus impact intensity on each other making the assumption of constant probability of propagation impractical. To this end, ICM seems to be more suitable for the scope of this paper than the SIR model.

Regarding ICM and LTM, they differ in the criteria utilized to decide on the success of the failure propagation in the network. For instance, LTM assumes that failure propagation to inactive nodes are dependent on the aggregated weight of all its active adjacent nodes as well as a threshold between zero and one generated using a uniform distribution (Wang 2014). Ultimately, failure propagates whenever the aggregated weight of adjacent nodes is greater than the threshold generated randomly for the inactive node under consideration (Pathak et al. 2010). On the other hand, ICM assumes that any failure propagation from one active node to another inactive node is (1) independent of the global failure state in the network; and (2) only dependent on the probability associated with the edge between them (Shakarian et al. 2015).

Because the fourth objective is to identify the cascade failure effect associated with various collaboration aspects on the overall collaboration on one hand and performance of modular construction on the other, there is a need to use a technique that assumes independent propagation mechanism such as ICM. The latter will allow for better investigation of the sensitivity of collaboration level and performance to the failure of various collaboration aspects. To this end, the authors used a cascading technique inspired by ICM and would provide detailed discussions on the associated assumptions and modeling techniques in the “Research Methodology” section.

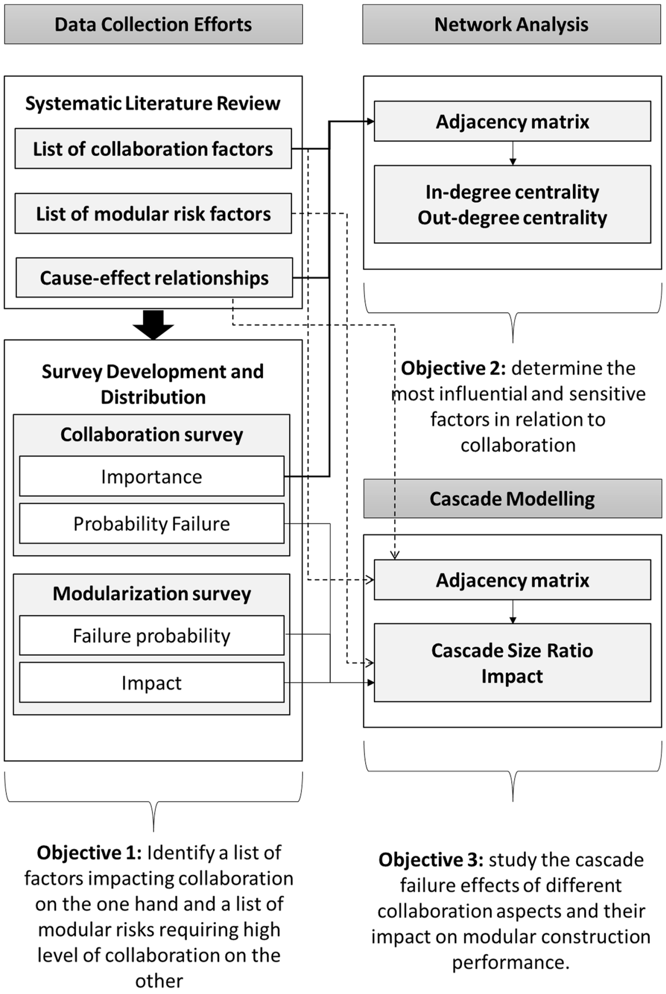

Fig. 1. Research methodology.

Research Methodology

The authors followed a multistep methodology, as shown in Fig. 1, comprising (1) systematic literature review, (2) survey development and distribution, (3) network analysis, and (4) cascade modeling.

Systematic Literature Review Analysis

In this paper, the authors need to utilize a network-based approach to investigate the cascading effects of collaboration in modular construction projects. As mentioned previously, any failure in one of the collaboration factors may propagate to other factors, leading to poor collaboration levels and subsequently triggering various modular risk events impacting the performance of the project. In fact, research has shown that collaboration and coordination among the various project stakeholders allow for better control and mitigation of various modular operations and risk factors (Zhai et al. 2014; Said 2015). Thus, in order to better investigate collaboration requirements in modular construction, there is a need to identify (1) the factors needed to establish strong collaborative working environment among the different parties of modular construction projects (i.e., collaboration factors); and (2) the modular construction operation risks that are directly impacted by the level of collaboration in the project (i.e., modular risks).

In addition, the authors need to determine the interactions among the various collaboration factors on the one hand and the relationship that connects them to the modular risks on the other (i.e., direct cause–effect relationships). To achieve that, the authors conducted a systematic literature review analysis using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) as follows:

- Database search: Scopus was used to perform the database search for collecting relevant articles. The search process was conducted using predefined keywords including “Collaboration,” “Coordination,” “Modular Construction,” “Modularization,” “Offsite,” and “prefabrication, preassembly modularization and offsite fabrication (PPMOF),” among others. Furthermore, the authors limited the database search to peer-reviewed journal articles in the engineering discipline. Based on the conducted search, a total of 136 articles were collected and considered for the next step of PRISMA.

Table 2. Selected articles for literature analysis

Publication year	References	Number of papers
2006–2011	Lee and Lee (2021), Essiz and Koman (2006), Hofman et al. (2009), and Van der Ham and Opedenakker (2023)	4
2012–2017	Han et al. (2017), Emuze and Smallwood (2014), Said (2015), Ramaji and Memari (2018), Bedair (2015), Han et al. (2015), Rahman et al. (2014), Arashpour et al. (2017), Khalili and Chua (2013), Jonsson and Rudberg (2014), Wong et al. (2017), and O'Connor et al. (2014)	12
2018–2022	Rahimian et al. (2019), Ezzeddine and de Soto (2021), Wuni et al. (2022), Shafiee et al. (2020), Dowsett et al. (2019), Banihashemi et al. (2018), Kirschke and Sietko (2021), Peltokorpi et al. (2018), Eriksson et al. (2021), Hegazy et al. (2020), Sun et al. (2020), Jang and Lee (2018), Abdul Nabi and El-adaway (2020, 2021), Pablo and London (2020), Mossman and Serhan (2021), Wuni and Shen (2020), and Yu et al. (2019)	18

- Screening process: Afterward, the authors conducted a preliminary screening process to the articles' titles and abstracts as to only include (1) peer-reviewed journal publications rather than books, conference papers, technical reports, and dissertations; and (2) articles fully or partially addressing collaboration in relation to modular construction projects rather than to other construction methods, construction sectors, or industries. Based on the aforementioned criteria, and after removing duplicated articles, a total of 46 articles were included to the next step of PRISMA.
- Full-article assessment: A full assessment of the remaining 46 articles was conducted. The full assessment allowed the authors to include articles discussing (1) modular construction operations and their dependence on project collaboration such as those related to safety, logistics, design, and so on; and (2) aspects of supply chain integration and coordination in modular construction projects.

Finally, the authors considered a total of 34 articles in the analysis of this paper as indicated in Table 2. By analyzing the articles presented in Table 2, the authors will achieve the first objective of this paper, which is identifying a list of collaboration factors, list of impacted modular risks, and their cause–effect relationships.

Survey Development and Distribution

In order to conduct network analysis and subsequently perform cascade modeling, the authors need to quantify (1) the importance of each collaboration factor, (2) the failure probability associated with each of the collaboration factors and modular risks, and (3) the modular risk impact on project performance. A detailed discussion on the reasoning behind the need for these data in the paper can be found in the "Network Analysis" and "Cascade Modeling" sections of the "Methodology" section. There is a need to first quantify the importance of each collaboration factor (represented as nodes) as well as the associated failure propagation probability. Although the importance was used to weigh the outward edges (i.e., outward causal relationships) between one factor and the other, the failure probability was used to simulate the propagation of failure among the various nodes of the networks.

Regarding modular risk factors, there is a need to collect failure probabilities as well as performance impact. Importance is only needed for collaboration factors because modular risks are child nodes rather than parent nodes (i.e., they do not have outward edges). Furthermore, the impact on project performance should be obtained for modular risks only because the impact of collaboration is mainly associated with the ability to control project risks and challenges, thus avoiding their impact on project performance.

Generally, using surveys for data collection should take into account the alignment of the respondents' expertise with the research topic under investigation (Tsehayae and Fayek 2014). For the scope of this paper, the authors are working on two intersected, yet distinct, topics requiring experience in collaboration on the one hand, and modular construction methods on the other. Therefore, there is a need to develop two different surveys addressing the two different disciplines that is collaboration and modularization. Various previous studies have adopted similar approach to collect data that addresses intersected yet different disciplines or areas (Tsehayae and Fayek 2014; Baral et al. 2023).

Because the identification of a potential pool of respondents possessing experience in both aspects may be challenging, the authors opted to develop two different surveys for data collection using an online platform called Qualtrics. Whereas the first survey aimed at collecting data related to the importance of collaboration factors and their associated failure probability, the second survey was used to collect data related to the failure probability of modular risks and their impact on project performance. Upcoming subsections provide detailed discussion on the development and distribution of both surveys.

Collaboration Survey

For the collaboration survey, it was developed to include the following sections: (1) respondent profile, (2) collaboration factor importance, and (3) failure probability of collaboration factors. In the first section, the respondents were asked to indicate their job position, stakeholder group, and years of experience in construction and collaboration. The second section asks the respondents to rate the importance of collaboration factors on a five-point Likert scale from 1 = very low to 5 = very high. Finally, the third section asks the respondents to rate the failure probability associated with each collaboration factor. Because the authors aim to use these probabilities as continuous values for the cascade modeling, the authors made sure to avoid inconsistencies in the respondents' understanding to the magnitudes associated with the rating scale. To this end, the authors adopted the five-point Likert scale established by the Construction Industry Institute (IPRA 2013), because each point on the scale is associated with a quantitative range of probabilities. The adopted unified scale is given in Table 3.

To control the data quality in this research, a purposive sampling approach was employed (Patton 1990). The directory of the Associated General Contractors (AGC) was used to obtain the survey population because it includes numerous project stakeholders with different company sizes, classifications, and locations in the US. Certain criteria were used to select the survey population by (1) choosing representatives possessing high experience and knowledge in collaborative project delivery methods; (2) selecting

Table 3. Adopted scale for the failure probability

Likert scale	Ranges
1	<10% probability
2	10% ≤ probability <35%
3	35% ≤ probability <65%
4	65% ≤ probability <90%
5	≥90% probability

Source: Data from IPRA (2013).
Note: P = probability of occurrence.

relevant stakeholders including consultants, general contractors, suppliers, and subcontractors; and (3) checking the profile of the companies to select those that adopt collaborative delivery methods.

The respondents of the collaboration survey did not necessarily possess experience in modularization. This is because the aim of this survey was to quantify the importance of collaboration factors in the construction industry and capture their probability of failures based on the current industry practices. Furthermore, the identification of experts experienced in both modular construction and collaboration was hard to achieve without compromising the quality of the experts' input. Ultimately, the results of the collaboration survey reflect the industry structure and practices in general when it comes to collaboration among stakeholders. As such, the survey was distributed to 235 construction practitioners, leading to the collection of 45 complete responses for further analysis. The latter corresponds to a total of 19.15% response rate.

Modularization Survey

For the modularization survey, it was developed to include the following sections: (1) respondent profile, (2) failure probabilities of modular risks, and (3) performance impact of modular risks. Similar to the collaboration survey, the first section asks the respondents to indicate their job position, stakeholder group, and years of experience in construction and modularization. The second section asks the respondents to rate the failure probabilities of the modular risks on the same Likert scale adopted in the collaboration survey (Table 3). Finally, the third section requests the respondents to rate the performance impact associated with modular risk factors. Similarly, the authors aim to use the impacts in the form of continuous values for the cascade modeling. To this end, the scale for the risk impact was also adopted from the International Project Risk Assessment (IPRA 2013). The adopted scale is presented in Table 4.

The authors followed a similar approach during the distribution process of the modularization survey as that of the collaboration survey. Thus, the directory of the AGC was used to obtain the survey population for modular construction. For this survey, the authors targeted respondents that have experience in the US construction industry on the one hand, and in modular construction methods on the other. Ultimately, the survey was distributed to a total of 190 respondents. Out of the 190, 45 responses were collected, reflecting a 23.07% response rate. The results of both surveys will be reported by computing the average scores across the respondents.

Table 4. Adopted scale for performance impact

Likert scale	Ranges
1	5% < cost and time growth
2	5% ≤ cost and time growth <10%
3	10% ≤ cost and time growth <20%
4	20% ≤ cost and time growth <50%
5	≥50% cost and time growth

Source: Data from IPRA (2013).
Note: I = impact.

Network Analysis

Network Building

Prior to the performance of network analysis, there is a need to build the network comprising of all the collaboration factors and their cause–effect relationships. Generally, networks can be either directed or undirected (Ahmat 2009). According to Caliandro (2022), directed networks allow for nonreciprocity in relationships among the factors or nodes of the network, whereas undirected networks always assume that relationships are mutual. In other words, unlike the latter, directed networks are mainly useful for capturing cause–effect relationships (Lee and Stohr 1985). Because the main goal of this paper is to investigate the cascade effect resulting from the failure of various collaboration-related aspects, there is a need to consider the cause–effect relationships among these different aspects. To this end, a directed network is more suited for the scope of this paper.

To develop the network, the authors need to transform the relationships derived from the systematic literature review into an unweighted adjacency matrix (Hummon and Doreian 1990). An unweighted adjacency matrix is a binary representation of the cause–effect relationships among the factors where a value of one indicates the presence of link between any two factors and zero indicates otherwise (Ramirez et al. 2016). To this end, the authors constructed the unweighted adjacency matrix A_u such that its rows and columns represent the factors and the entries of the matrix represent the presence of a link between the cell's corresponding factors. In other words, if the entry a_{uij} is equal to one, it means that factor i affects factor j. Because the factors cannot impact themselves, all diagonal entries are considered zeros. Finally, the adjacency matrix A_u was constructed as to include all the collaboration factors.

According to Parker and McEachen (2016), the unweighted adjacency matrix A_u only represents the existence of links without providing any additional information about their quality and influence. Thus, for a better understanding of the important collaboration aspects, there is a need to take into consideration the number of associated cause–effect relationships (i.e., A_u) as well as the importance/quality of these factors in promoting collaboration. To this end, the authors used the average importance rates retrieved from the collaboration survey to reflect the quality of the links associated with each collaboration factor. In other words, the weighted adjacency matrix A_w is developed as shown in Eq. (1)

$$A_w = \begin{cases} a_{wij} = w_i & \text{if } a_{uij} = 1 \\ a_{wij} = 0 & \text{if } a_{uij} = 0 \end{cases} \tag{1}$$

where a_{uij} = entries of the unweighted adjacency matrix with a value of one, indicating a link between factors i and j and a value of zero otherwise; a_{wij} = entries of the weighted adjacency matrix; and w_i = average importance rate associated with factor i. In other words, factors rated with a higher average importance rate will possess a higher effect on the impacted factors.

Centrality Measures

By developing A_w, the authors will be able to visualize and analyze the weighted network using the Gephi software version 0.10.1 package. For network analysis, there are various centrality measures that can be used to assess the importance of the network nodes, such as degree centrality, in- and out-degree centralities, betweenness centrality, and network density, among others (Lee et al. 2018). However, for this paper, the authors are more interested in investigating the most influential and sensitive factors as related to collaboration in modular construction projects. To this end, the authors considered only two centrality measures: in-degree and out-degree centralities. In directed networks, in-degree centrality is the summation of the inward weighted edges [Eq. (2)], whereas out-degree centrality is the summation of the outward weighted edges [Eq. (3)] (Hassan et al. 2022)

$$D_{\text{in}} = a_{wj} = \sum_i a_{wij} \tag{2}$$

$$D_{\text{out}} = a_{wi} = \sum_j a_{wij} \tag{3}$$

where D_{in} and D_{out} = in- and out-degree centralities respectively; a_{wj} = summation of the entries of the jth column of A_w; and a_{wi} = summation of the entries of the ith row of A_w.

Cascade Modeling

ICM

To simulate the cascade failure effect in the network, the authors followed the assumptions of the ICM as depicted by Shakarian et al. (2015) and Wang (2015):

- The system is modeled as a network graph $G = (N, E)$ where N indicates the nodes representing the collaboration factors and E denotes edges representing their relationships. For this paper, G represents the network developed from the weighted adjacency matrix A_w.
- Any node has two states, either active or inactive. For the scope of this paper, an active node indicates that the corresponding collaboration factor has failed, whereas an inactive node indicates otherwise.
- Any node in the network can only change from inactive to active.
- Failure propagation between each pair of connected nodes $i \rightarrow i$ occurs with a probability $P_{i,j}$.
- Propagation occurs in discreet time steps.
- In the first time step, an initial set of nodes is activated to start the propagation process in the network.
- Each activated node i in the initial set have a single chance to activate each of its neighboring nodes j with a predefined and unique probability $P_{i,j}$
- If i succeeds to activate j, then j becomes activated and can activate its set of neighboring nodes in the next time step. If i does not succeed to activate j, it does not have another attempt to propagate failure to j. The process continues until no further propagation attempts are possible.

Model Inputs

In order to perform the steps depicted in the previous subsection, the authors need to establish the input of the cascade model including (1) the initial set of activated nodes, and (2) the propagation probability between each pair of connected nodes. However, because the authors aim to capture the performance impact associated with the cascade failure of various collaboration aspects, the impacts associated with each modular risk were also included as an input to the model.

Initial Set of Activated Nodes. For the scope of this paper, the authors determined a list of collaboration factors categorized under different broad themes or aspects. Therefore, to ensure more efficient analysis, the authors established the initial set of activated nodes based on the identified collaboration aspects. For instance, if a collaboration theme $S = \{s_1, \ldots, s_k\}$ comprising of k number of factors or nodes, the authors investigated its associated cascade failure effect by assuming the corresponding collaboration factors as initially active.

Propagation Probabilities. These were derived from the quantitative data collected from the survey. The average failure probabilities on the 1–5 scale were derived for the collaboration factors (collaboration survey) and modular risks (modularization survey). However, there is a need to transform the ordinal probabilities into continuous numerical values. To this end, the authors interpolated the obtained average probabilities based on their respective ranges depicted in Table 4 such that an average probability between zero and one corresponds to a range between 0% and 10%, that between one and two corresponds to range of 10% to 35%, and so on.

Ultimately, upon interpolation, the authors are able to assign a failure probability for each of the collaboration factor and modular risk. However, the propagation probability $P_{i,j}$ from node i to node j should not only depend on the failure probability P_j of node j but rather on the relative weight of the i, j edge itself. To this end, the authors further used A_w to develop a normalized adjacency matrix NA_w as shown in Eq. (4)

$$NA_w = \begin{cases} na_{wij} = \dfrac{a_{wij}}{\sum_i a_{wij}} & \text{if } a_{uij} = 1 \\ na_{wij} = 0 & \text{if } a_{uij} = 0 \end{cases} \tag{4}$$

where na_{wij} = normalized weight of the edge $i \rightarrow j$; and a_{wij} = average importance derived for node i [Eq. (1)]. Ultimately, by performing Eq. (4), the authors assume that—considering four nodes affecting node j—the sum of the weights of the four edges coming inward to node j is equal to one. Once the weights and failure probabilities of each node were derived, the propagation probability $P_{i,j}$ from node i to node j is computed as shown in Eq. (5)

$$P_{i,j} = na_{wij} \times P_j \tag{5}$$

Performance Impact. The average performance impact on a 1–5 scale were derived for the modular risk factors (modularization survey). However, similar to the probabilities, there was a need to transform the ordinal impact into continuous numerical values. To this end, the authors interpolated the obtained average impacts based on their respective ranges depicted in Table 4 such that an average impact between zero and one corresponds to a range between 0% and 5%, that between one and two corresponds to range of 5% to 10%, and so on.

Simulation Model

The main aim of the cascade effect analysis is to simulate failure propagation across the various collaboration related aspects in the network and then investigate their impact on modular construction performance. The authors developed the cascade simulation model as depicted in Fig. 2.

The authors investigated cascade effect in case of different failure scenarios wherein each scenario a collaboration theme is activated. Thus, for each scenario, the initial set of activated nodes S includes the factors associated with one of the identified collaboration themes. Once the initial set of activated nodes are determined, a simulation model with 1,000 runs was developed. For each run in the simulation model, the set of target nodes T associated with each node in the initial set of activities nodes are retrieved from adjacency matrix NA_w along with their edge probabilities computed using Eq. (5).

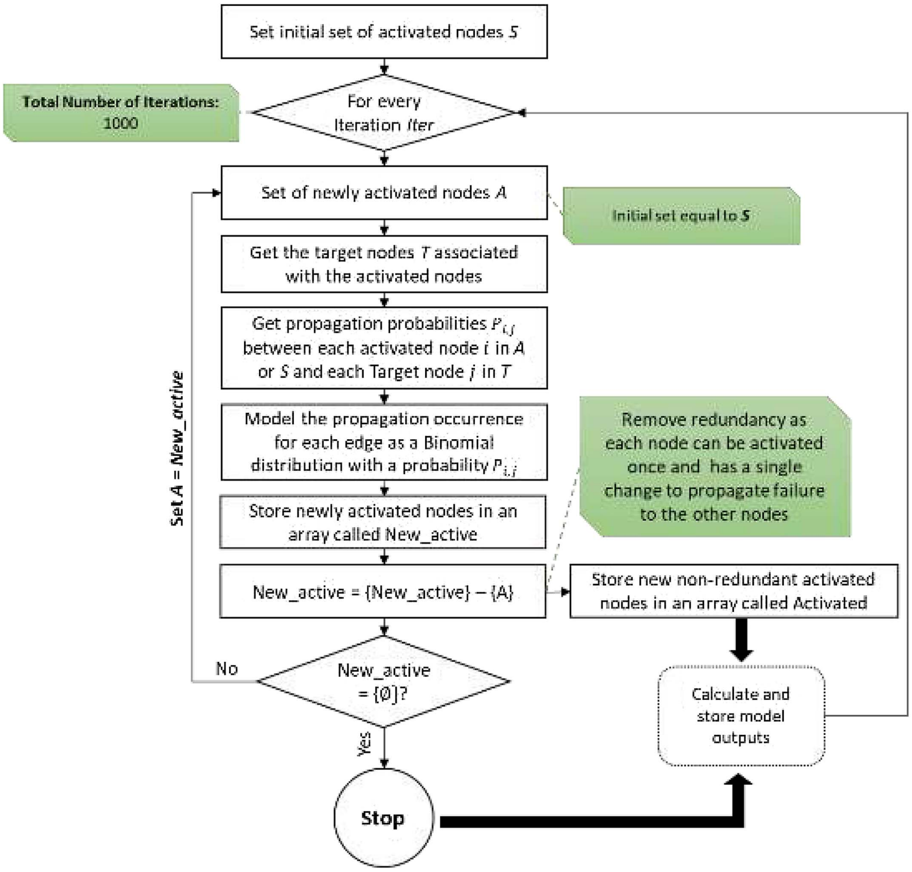

Fig. 2. Developed cascade simulation model.

Ultimately, an activated node i in S can activate a target node j in T with a probability $P_{i,j}$. Thus, the successful propagation between i and j (i.e., activation of j) is modeled as a binomial model with a parameter $P_{i,j}$ where a returned value of one indicates a successful propagation and a value of zero indicates otherwise. Upon identifying the activated nodes, the model stores them and repeat the process while ensuring that no redundant activated nodes are simulated. The latter is important to ensure that each node has only one chance to activate its neighbors. In case no new nonredundant nodes were activated, the propagation progress stops.

Once propagation process stops, the set of activated collaboration factor nodes—excluding those included in the initial set of activated nodes S—are stored to calculate the model outputs including (1) cascade size ratio across the whole network, (2) cascade size ratio across each theme, and (3) captured performance impact. Once the model outputs are calculated and stored, the same logic repeats until a total of 1,000 runs are executed. The next subsection provides a detailed discussion on model output calculation.

Model Outputs

In order to understand the cascade effect associated with the failure of different collaboration aspects, the authors need to determine the proportion of nodes that were affected by the failure of collaboration factors included in the initial set (i.e., cascade size ratio). Furthermore, it is interesting to investigate how the failure in one of the collaboration themes propagates to other collaboration themes. To this end, the authors further calculated the cascade size ratio across each collaboration theme. Ultimately, the cascade size ratio across the whole network and the various collaboration themes are computed using Eqs. (6) and (7), respectively (Doo and Liu 2014)

$$\text{Cascade size}(S_c) = \frac{\text{No. of activated nodes}}{\text{Size of } NA_w - \text{Size of } S_c} \tag{6}$$

$$\text{Cascade size}(S_c \rightarrow S_r) = \frac{\text{No. of activated nodes in } S_r}{\text{Size of } S_r} \tag{7}$$

where $\text{Cascade size}(S_c)$ and $\text{Cascade size}(S_c \rightarrow S_r)$ = cascade size ratios of collaboration theme S_c across the whole network and other collaboration themes S_r, respectively; Size of NA_w and Size of S_c = total number of nodes in the network and the initial set of activated nodes of collaboration theme S_c; and Size of S_r = number of nodes in collaboration theme S_r.

Upon investigating the cascade size ratios, the objective is to also capture the performance impact associated with the failure of the various collaboration themes. Thus, the performance impact is calculated by first modeling the occurrence of the modular risks as a binomial model with a probability P. First, the individual edge probabilities affecting the corresponding modular risks are compute using Eq. (5). Afterward, P is calculated by simply summing the edge probabilities associated only with the activated nodes. Ultimately, the impact is calculated summing the interpolated impact values associated with the activated modular risks.

Results and Analysis

Systematic Literature Review Analysis: Collaboration Factors, Modular Risks, and Cause–Effect Relationships

Based on the systematic literature review analysis, the authors identified a total of 25 factors that impact collaborative working

Table 5. Identified collaboration factors and their cause–effect relationships

Themes	ID	Factors	Impact factors
Project organization and contract	F1	Incentives	F10
	F2	Contract drafting and conditions	F1, F3, F10, F15, F22
	F3	Efficient risk allocation	F11
	F4	Project delivery method selection	F2, F5, F7
	F5	Early involvement of contractors, subcontractors, and manufacturers	F12, F20, F21, F24
Stakeholder relationships and characteristics	F6	Team workshops and training	F8
	F7	Prequalification and team selection	F8
	F8	Project team skill, knowledge, and experience	F15, F20, F21, F22, F23
	F9	Stakeholders' leadership and management support	F6, F11, F12
	F10	Commitment and willingness for collaboration and cooperation	F13, F14, F16
	F11	Trust	F10, F22
	F12	Integration and alignment on project goals	F10, F23
Information sharing, documentation, and technologies	F13	Investment on interoperability of adopted information technologies	F15, F17
	F14	Integration of advanced technologies and visualization tools	F15, F17, F18
	F15	Building information modeling effectiveness	F17, F18, F19, F25
	F16	Efficiency and frequency of meetings	F19, F20, F21, F25
	F17	Effectiveness of communication and information sharing	F18, F19, F20, F21, F22, F25
	F18	Timely reporting and efficient trackability	F25
Design and construction planning	F19	Design coordination	F23
	F20	Risk management	None
	F21	Constructability feedback	F23
	F22	Lean construction practices	None
	F23	Efficiency and feasibility of design	None
	F24	Standardization	F22, F23
	F25	Construction coordination	F20

environment in construction projects. Furthermore, the authors identified the cause–effect relationships among these factors. Table 5 details the identified collaboration factors and their cause–effect relationships. The referenced sources for the identified collaboration factors and associated relationships are included in Table S1. As indicated in Table 5, these 25 factors were categorized under four different themes including (1) Project organization and contract, (2) Stakeholders' relationships and characteristics, (3) Information sharing, documentation, and technologies, and (4) Design and construction planning.

Regarding the modular risks, the authors were able to identify a list of 10 different factors. These risks are associated with the various modular construction aspects that are impacted by the level of collaboration in the project such as safety planning, site attributes and layout, tolerance and interfacing, among others. Ultimately, the 10 modular risks are presented in Table 6, along with the set of impacting collaboration factors present. The referenced sources supporting the identified modular risks and their direct dependence on the collaboration factors are present in Table S2. The systematic literature review analysis showed that not all collaboration factors directly impact the modular risks. The latter explains having only 7 out of the 25 collaboration factors affecting the modular risks. Furthermore, although all modular risks get impacted by the collaboration factors, the opposite does not hold true. The latter aligns with the fact that the level of collaboration is perceived to impact project performance through promoted risk mitigation in modular construction projects.

The lack of a direct causal relationship between a collaboration factor and a modular risk does not indicate the lack of complete impact. However, it actually reflects that a failure associated with that collaboration factor does not directly trigger the occurrence of a modular risk in the project. However, there could be an indirect relationship reflected by a cascading propagative effect among the collaboration factors leading up to the modular risks. The latter explains the motivation of the authors to perform cascade modeling as to capture the direct and indirect effects of the various collaboration-related aspects. Ultimately, the establishment of the collaboration factors, modular risks, and their direct causal relationships is the basis of the analysis and thus impacting the developed network and cascading model.

Table 6. Identified modular risks and their associated impacting collaboration factors

ID	Risk factors	Impacting collaboration factors
R1	Inefficient assembly and installation equipment	F20, F23
R2	Inefficient transportation planning	F20, F23
R3	Inadequate site logistics	F18, F20, F22, F23, F25
R4	Rework	F8, F23, F25
R5	Inefficient material and waste management	F22, F23, F24
R6	Inadequate activity sequencing and management	F18, F20, F22, F24, F25
R7	Late design changes	F19, F20, F23
R8	Poor safety planning	F20, F23, F25
R9	Poor productivity	F8, F23, F25
R10	Inadequate tolerance and interfacing	F15, F20, F23

Survey Results

Respondent Profile

In relation to the collaboration factors, the respondents represented the different stakeholder groups including upstream

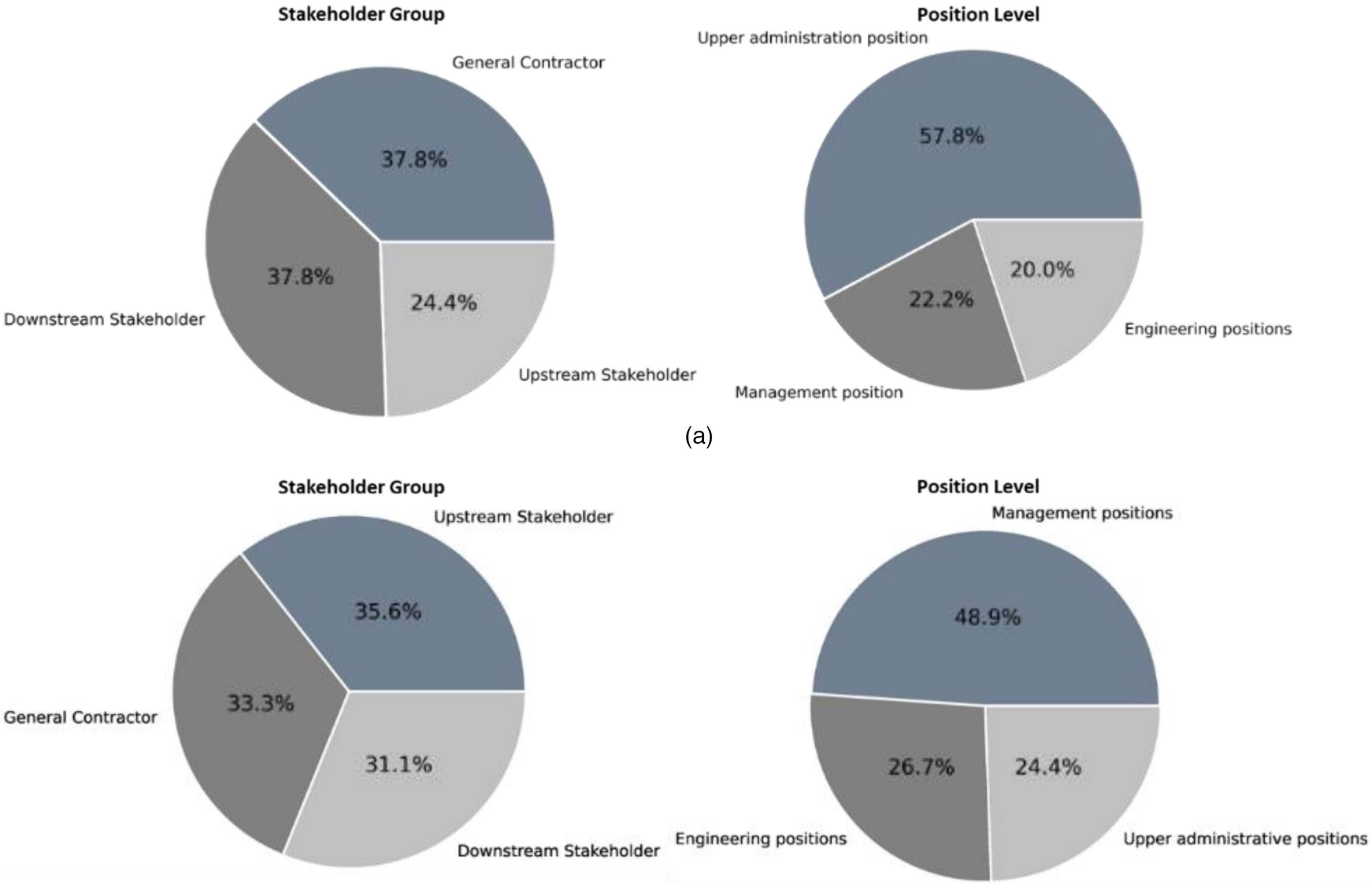

Fig. 3. Respondent profiles: (a) collaboration survey respondents; and (b) modularization survey respondents.

(owners, designers, and consultants), downstream (subcontractors, suppliers, and manufacturers), and general contractors. As shown in Fig. 3(a), the stakeholder distribution of the collaboration survey participants consisted of 24.4% upstream stakeholders, 37.8% general contractors, and 37.8% downstream stakeholders. Furthermore, the participants possessed various position levels including upper management positions (i.e., program directors, vice presidents, and chief executive officers), management positions (i.e., lean managers, project managers, operation managers, and so on), and engineering positions (i.e., project engineers, structural engineers, field engineers, and so on). For the collaboration survey, the positions of most of the respondents possessed upper administration positions (57.8%) in their respective companies. Such characteristics indicate that the survey data represent views of subject matter experts who hold authoritative and decision-making roles in both the project and corporate levels.

For the collaboration survey, the authors collected data from respondents having an average experience in construction of 27.04 years, and 18.22 years in collaborative planning. Tables 7 and 8 present the average respondents' experience in construction and collaboration across stakeholders' group and position level, respectively. As indicated in Table 7, all stakeholders group have high experience in construction (i.e., 19 years and above). Furthermore, all stakeholders had significant experience in collaborative project delivery methods (i.e., 15 years and above). Regarding Table 8, the respondents of the various position levels possessed high experience in construction (i.e., 30.08 years and above) and in collaboration (14 years and above). Ultimately, the results show that the respondents reflect high experience in the construction industry as well as collaborative project delivery methods adopted in the industry. The latter ensures that the results obtained from the respondents are valid and reliable.

Regarding the modularization survey respondents, Fig. 3(b) shows that the participants represent all the various stakeholders'

Table 7. Average experience per stakeholder groups for collaboration survey

	Average years of experience	
Stakeholder	Construction	Collaborative project delivery
Upstream stakeholder	19.36	15.73
General contractor	31.53	20.76
Downstream stakeholder	27.53	17.29

Table 8. Average experience per position level for collaboration survey

	Average years of experience	
Position level	Construction	Collaborative project delivery
Upper administrative positions	30.08	23.08
Management positions	28.90	14.40
Engineering positions	16.22	8.44

Table 9. Average experience per stakeholder groups for modularization survey

	Average years of experience	
Stakeholder	Construction	Modular construction
Upstream stakeholder	25.63	13.44
General contractor	26.00	15.13
Downstream stakeholder	22.86	14.36

Table 10. Average experience per position level for modularization survey

	Average years of experience	
Position level	Construction	Modular construction
Upper administrative positions	32.55	10.45
Management positions	22.14	14.23
Engineering positions	17.92	17.92

groups as well. In addition, most of the participants possessed management and administrative positions reflecting their expertise in construction on one hand, and modularization on the other. The respondents possessed an average of 24.9 years of experience in construction, and 14.29 years in modular construction methods.

Tables 9 and 10 detail the average respondents' experience in construction and modularization across stakeholders' group and position level, respectively. As indicated in Table 9, all stakeholders group had high experience in construction (i.e., 22 years and above). Furthermore, all stakeholders had significant experience in modularization (i.e., 13 years and above). As indicated in Table 10, the respondents of the various position levels possessed high experience in construction (i.e., 17 years and above) and in modularization (14 years and above). Ultimately, the results show that the respondents reflect high experience in the construction industry as well as modular construction methods. The latter ensures that the results obtained from the respondents are valid and reliable.

Sample Size Sufficiency

The sufficiency of the survey response rate was tested using a statistical technique developed by Cochran (1977). In addition, various previous research works used the same technique to check the sample sufficiency of their data (Abdul Nabi and El-adaway 2021; Pereira et al. 2018; Fellows and Liu 2015; Srour et al. 2017). The needed sample size for both of the developed surveys is computed as shown in Eq. (8)

$$n = \frac{(t^2)(s^2)}{(e^2)} \tag{8}$$

where t = Z-statistic of the significance level (α); n = minimum required sample size; e = scale point, which is 5, multiplied by the adopted margin of error, which is 0.05 for this paper (Assaad et al. 2020); and s = estimate of variance associated with the used scale. It is usually obtained by dividing the range of the scale over the number of standard deviations for nearly all potential values of such range. Similar to multiple previous research works, a significance level of 95% was used for this test, where α is 0.05 (Assaad et al. 2020; Kamali and Hewage 2017). The t value, associated with significance level of 95%, is 1.96 (Kamali and Hewage 2017; Pereira et al. 2018). The s value, associated with the used five-point Likert scales, is $5/6$ (Fellows and Liu 2015). Additionally, with a five-point Likert scale and a 5% margin of error, the e value is (5×0.05). To this end, the value of n is 43

$$n = \frac{(1.96^2)\left(\frac{5^2}{6}\right)}{(5 \times 0.05)^2} = 42.68 \approx 43$$

Therefore, a total of 45 responses in both surveys is considered sufficient for the analysis of this paper.

In addition to the statistical verification, the sufficiency of the sample size was verified empirically by cross-checking the number of responses with relevant studies in construction engineering and management field that had similar sample sizes including—among others—the work of (1) Atakul and Ergonul (2022) with a total of 42 responses, (2) Gurmu and Aibinu (2018) with a total of 39, (3) O'Connor and Woo (2017) with a total of 36, (4) Akroush and El-adaway (2017) with a total of 30, (5) Vyas et al. (2019) with a total of 42, and (6) Votano and Sunindijo (2014) with a total of 45 responses.

Collaboration Survey Results

Using the survey results, and as indicated in Table 11, the authors quantified the importance of the different factors impacting collaboration and the associated failure probability in the construction industry.

The results indicate that the project organization and contract-related factors have the highest importance in promoting collaboration in construction projects; whereas information sharing, documentation, and technologies were associated with the lowest average importance. In addition, the top collaboration factors that impact collaboration include (1) F10: Commitment and willingness for collaboration and cooperation, (2) F5: Early involvement of contractors, subcontractors, and manufacturers, (3) F11: Trust, (4) F7: Prequalification and team selection, and (5) F12: Integration and alignment on project goals.

On the other hand, the relatively less important factors include: (1) F22: Lean construction practices, (2) F6: Team workshops and training, (3) F15: Building information modeling effectiveness, (4) F16: Efficiency and frequency of meetings, and (5) F13: Investment on interoperability of adopted information technologies.

It can be noted from the results that F22 was rated the lowest. In fact, efficient implementation of lean practices certainly demands high level of collaboration among the project stakeholders (Johansen and Walter 2007). However, the opposite may not apply because effective collaboration may not necessitate the use of lean construction practices and methods. The latter aligns with the results of the systematic literature review analysis where lean construction practices were found to have no impact on any other collaboration factors. On the other hand, the low importance score for F15 and F13 was unexpected because these factors are considered vital for effective communication and information sharing (F17), whose importance score, in turn, is considered high (ranked sixth). Therefore, it is crucial to investigate the importance of collaboration factors not only based on their individual importance, but also on their interactions on other factors.

The theme associated with the high probability of failure in the construction industry is also associated with the project organization and contract, whereas the theme with the lowest probability of failure is related to information sharing, documentation, and technologies. However, the collaboration factors with the highest failure probability in the construction industry are associated with (1) F5: Early involvement of contractors, subcontractors, and manufacturers, (2) F25: Construction coordination, (3) F19: Design coordination, (4) F17: Effectiveness of communication and

Table 11. Average importance and probability of failure associated for each collaboration factor and theme

		Importance			Theme importance		Failure probability			Theme failure probability	
Themes	ID	Average	SD	Rank	Average	Rank	Average	SD	Rank	Average	Rank
Project organization and contract	F1	4.11	0.79	10	4.11	2	2.78	1.09	14	2.88	1
	F2	4.05	0.67	16			2.87	0.98	9		
	F3	3.90	0.76	18			2.73	1.02	17		
	F4	4.10	0.79	12			2.76	0.95	16		
	F5	4.40	0.85	2			3.24	1.01	1		
Stakeholder relationships and characteristics	F6	3.60	0.89	24	4.18	1	2.58	1.04	24	2.76	3
	F7	4.30	0.78	4			2.91	1.01	7		
	F8	4.24	0.80	7			2.60	1.04	23		
	F9	4.06	0.81	14			2.80	1.02	12		
	F10	4.41	0.76	1			2.89	1.04	8		
	F11	4.37	0.96	3			2.82	1.12	10		
	F12	4.25	0.79	5			2.69	1.05	19		
Information sharing, documentation, and technologies	F13	3.75	0.83	21	3.86	4	2.82	1.00	11	2.72	4
	F14	3.76	0.81	20			2.62	1.02	20		
	F15	3.62	1.06	23			2.60	1.18	22		
	F16	3.65	0.75	22			2.20	1.02	25		
	F17	4.25	0.81	6			3.03	0.96	4		
	F18	4.13	0.75	9			3.02	0.91	5		
Design and construction planning	F19	4.11	0.72	11	3.99	3	3.07	1.08	3	2.87	2
	F20	4.02	0.77	17			2.78	1.07	15		
	F21	4.10	0.91	13			2.71	1.15	18		
	F22	3.57	0.94	25			3.00	0.94	6		
	F23	4.05	0.84	15			2.62	0.95	21		
	F24	3.87	1.00	19			2.80	0.96	13		
	F25	4.22	0.82	8			3.11	0.97	2		

Note: SD = standard deviation.

information sharing, and (5) F18: Timely reporting and efficient trackability.

On the other hand, the relatively lowest failure-prone collaboration factors in the construction industry include: (1) F16: Efficiency and frequency of meetings, (2) F6: Team workshops and training, (3) F8: Team skill, knowledge, and expertise, (4) F15: Building information modeling, and (5) F23: Efficiency and feasibility of design. All themes have close average failure probabilities because the factors that are highly failure-prone are spread over factors from different themes. However, two collaboration factors in the Information sharing, documentation, and technologies theme have the highest probability of failure in the industry. Despite being associated with the lowest theme, the latter still indicate that poor communication, as well as information sharing and documentation, is common in the construction industry in impeding the ability to promote adequate collaborative working conditions.

Modularization Survey Results

From this survey, and as indicated in Table 12, for each modular risk, the authors quantified (1) the corresponding probability of occurrence; and (2) impact on performance. To this end, the modular risks with the highest failure probability include (1) R3: Inadequate site logistics, (2) R7: Late design changes, and (3) R10: Inadequate tolerance and interfacing. The modular risks with the highest impact on project performance include: (1) R10: Late design changes, (2) R3: Inadequate site logistics, and (3) R6: Inefficient activity sequencing and management.

Ultimately, the results align with the literature in relation to the criticality of the aforementioned modular construction operations. For instance, modular design is inflexible to late design changes (Jaillon and Poon 2010), and thus design errors/omissions, and owner-directed changes have a great impact on performance of modular construction projects (Goh and Loosemore 2017). The latter emphasize on the need for extensive coordination during the design phase among owner, designers, engineers, and contractors to avoid design errors or constructability problems (Tam and Hoa 2014).

In addition, modular construction methods possess specific demands in relation to site logistics (Zhai et al. 2014). These attributes include site layout, availability of storage, accessibility of transport/lifting equipment and cranes, and suitability of soil conditions (Khalili and Chua 2013). Ultimately, as part of the design feasibility, there is a need to determine the optimal configuration that aligns the design of the modules to the site attributes and logistics constraints. In addition to site logistics, tolerance-related issues are

Table 12. Average probability of occurrence and performance impact with each modular risk factor

	Probability of occurrence			Performance impact		
ID	Average	Standard deviation	Ranking	Average	Standard deviation	Ranking
R1	2.200	1.046	10.000	3.22	1.11	7
R2	2.222	0.986	9.000	3.04	0.94	8
R3	3.733	0.929	1.000	3.61	0.95	3
R4	2.622	0.973	6.000	3.51	1.16	5
R5	2.467	1.108	7.000	2.77	1.06	10
R6	3.111	1.120	4.000	3.70	1.06	2
R7	3.511	1.147	2.000	3.80	1.11	1
R8	2.289	0.885	8.000	2.93	1.15	9
R9	2.778	1.030	5.000	3.44	1.02	6
R10	3.178	0.950	3.000	3.53	1.09	4

perceived to have a great impact on modular construction projects (Abdul Nabi and El-adaway 2021). Therefore, it is crucial to manage tolerance-related issues during the design by involving fabricators or manufacturers that are skilled in tight tolerance, and avoiding the excessive use of small modules. (Isaac et al. 2016; O'Connor et al. 2014). Furthermore, adequate synchronization between off-site and onsite activities requires a high level of communication and collaboration among the project parties (Jonsson and Rudberg 2015).

Network Analysis

Upon data collection, the authors utilized the collaboration factors, and their cause–effect relationships to construct a weighted adjacency matrix A_w. Fig. 4 shows the collaboration network associated with A_w consisting of the 25 nodes (collaboration factors) and 56 directed edges. The intensity of the nodes' colors are directly proportional to their corresponding in-degree centrality D_{in}, and the nodes' sizes are directly proportional to their corresponding out-degree centrality D_{out}. Thus, the darker the node, the higher the sensitivity of the collaboration factor is to other factors in the network. On the other hand, the larger the node, the higher the impact of the collaboration is on other factors in the network. For conciseness, the authors presented only the networks in Fig. 4. However, the values of the in- and out-degree centralities are presented along with the corresponding factor's rankings in Table S3.

As shown in the graph, the collaboration factors that have the highest influence on other factors in the network (i.e., the ones they impact the overall level of collaboration in the project) have the largest size nodes. These nodes include (1) F17: Effectiveness of communication and information sharing, (2) F8: Team skill, knowledge, and expertise, (3) F2: Contract drafting and conditions, (4) F5: Early involvement of contractors, subcontractors, and manufacturers, (5) F16: Efficiency and frequency of meetings, and (6) F15: Building information modeling effectiveness. Ultimately, the network analysis shows that three of the top influential collaboration factors fall within the Information sharing, documentation, and technologies theme. In fact, interesting contradiction between the collaboration survey and network analysis was noticed, particularly in relation to F16: Efficiency and frequency of meetings. Although the industry experts considered such factor from the least important ones (ranked 22 based on importance rate), the network analysis showed that F16 has a great impact on other factors in the network. In other words, any deficiency related to F16 can have great impact on many other aspects of collaboration in the project. Ultimately, the latter aligns with the motivation of this paper, which is considering not only the importance of each factor but also their interdependence with others.

Regarding the collaboration factors with the highest in-degree (i.e., the ones having high sensitivity to other collaboration factors), they include (1) F22: Lean construction practices, (2) F20: Risk management, (3) F23: Efficiency and feasibility of design, (4) F10: Commitment and willingness for collaboration and cooperation, (5) F21: Constructability feedback, and (6) F15: Building information modeling effectiveness. Therefore, the results show that collaboration aspects related to design and construction planning theme are the most sensitive factors.

Another interesting finding is having F10 (commitment and willingness for collaboration and cooperation) as one of the highest sensitive factors to other collaboration factors. The latter indicates that the commitment of project stakeholders is influenced by various factors and aspects in the project. Furthermore, F10 is not only considered sensitive (ranked fourth based on in-degree) but also influential for many other factors (ranked seventh based on out-degree). In fact, the results align with the industry's experts whose average important rates of F10 was ranked first among all factors. Ultimately, the network analysis reflect the propagative effect of the collaboration factors' network, where a failure in one of the collaboration aspects may have a cascade effect on other aspects, leading to inadequate collaboration and subsequently impact modular construction implementation in the project.

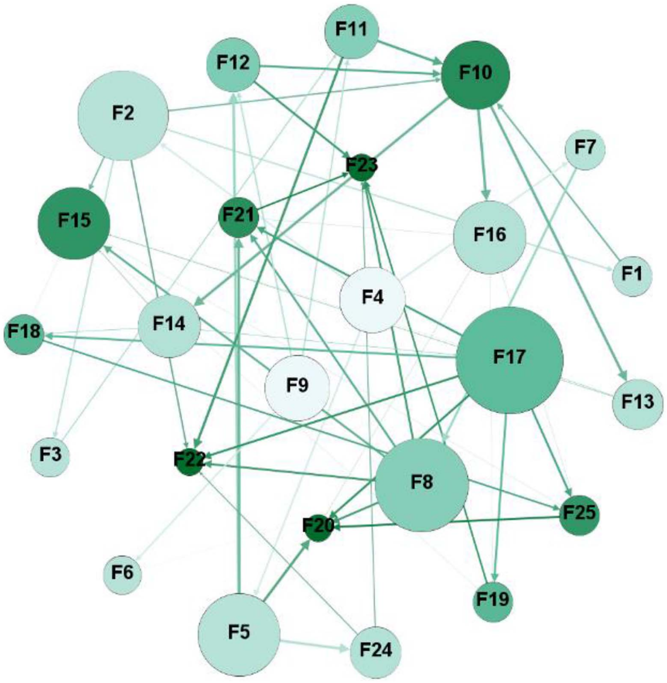

Fig. 4. Directed network work depicting collaboration factors and their cause–effect relationships.

Cascade Modeling

The authors performed cascade modeling for four different scenarios wherein each scenario a collaboration theme is considered active or failed to start the failure propagation process. For each collaboration theme or scenario, the factors as presented in Table 5 were activated and included in the initial set of activated nodes. Furthermore, the failure probabilities were interpolated for the collaboration factors and modular risks as depicted in the "Methodology" section, and they are presented in Table S4. Afterward, the authors computed the propagation probabilities associated with each edge in the network using Eq. (5) (Fig. S1). Furthermore, and to capture the impact of the collaboration failure cascade on modular construction implementation, the impact of modular risks were also interpolated (Table S5). The results of the cascade model are presented in the "Cascade Size Ratios" and Performance Impact" subsections.

Cascade Size Ratios

The results of the cascade size ratio indicates the influence of each theme on the overall collaboration in the project. Thus, the higher cascade size ratio, the more influential the corresponding theme on achieving adequate collaborative working in the project. Table 13 presents the results of the cascade model in terms of the cascade size ratio across the entire network on the one hand, and each collaboration theme on the other.

As shown in the table, the themes possessed approximately equal influence degree on the overall collaboration level in the

Table 13. Results of the cascade model

Theme ID	Collaboration theme	Initial set of activated nodes	Cascade size ratio	Cascade size ratio per theme			
				T1	T2	T3	T4
T1	Project organization and contract	F1, F2, F3, F4, and F5	0.269	—	0.25	0.17	0.22
T2	Stakeholder relationships and characteristics	F6, F7, F8, F9, F10, F11, and F12	0.280	0	—	0.38	0.18
T3	Information sharing, documentation, and technologies	F13, F14, F15, F16, F17, and F18	0.183	0	0	—	0.26
T4	Design and construction planning	F19, F20, F21, F22, F23, F24, and F25	0.275	0	0	0	—

project except for Information sharing, documentation, and technologies with a cascade ratio of 0.183. Ultimately, the results emphasize the importance of all themes to achieve collaboration in modular construction projects. Thus, a failure in any of the identified aspects can impact the collaborative working environment among the various stakeholders. For better understanding of the cascade effect among the collaboration themes, the cascade size ratio across each theme was also computed using Eq. (6). The results also show that although a failure in project organization and contract-related aspects can propagate to all other themes, the opposite does not hold true. The latter is reflected in the fifth column of Table 13, where all values are zero. On the other hand, a failure in design and construction planning-related aspects does not propagate to any other collaboration theme but rather is dependent on their efficiency. This can be noticed by having all entries of the fifth row in Table 13 equal to zero.

Ultimately, when analyzing the results, a careful interpretation should be considered by taking the chain effect and interdependence among the various themes. For instance, Project organization and contract has notable influence on other collaboration themes, more particularly Stakeholder relationships and characteristics, which, in turn, greatly influences Information sharing, documentation, and technologies. The latter further influences Design and construction planning. Ultimately, the results clearly suggest that ensuring collaboration needs early decision making in relation to project organization and contract as well as stakeholder relationships and characteristics. These decisions should, in turn, affect information sharing, documentation, and technologies and subsequently the design and construction planning phase of modular construction projects. The collaboration themes that do not have direct causal relationships with modular risk factors were found to have the highest cascade ratios. This re-emphasizes on the importance of the early collaboration and decision-making factors and their indirect impact on the control of modular risks during project implementation.

Performance Impact

The performance impact shows the direct impact of the theme on the performance of modular construction methods. In other words, the higher the performance impact, the more direct the impact that theme has on modular construction implementation in the project. However, having low direct impact does not indicate that the theme is not important but rather show that the collaboration-related factors do not directly impact the implementation process of modular construction methods. The results are shown in Fig. 5.

Ultimately, the direct impact on performance seems to be small for the aspects that demand early decisions, such as establishment of project organization and contract drafting (13.2%) and stakeholder selection and relationships (21.40%), as well as information sharing mechanisms and technologies (25.30%). However, the direct impact of collaboration tremendously increases during design and construction planning, with 70.6% performance impact. The latter indicates that collaboration-related factors associated directly with project execution phase have the highest performance impact. Thus, the benefits of collaboration in modular construction projects are mainly captured during design and construction planning.

However, the ability to ensure efficient design and construction planning depends on early collaboration decisions. For instance, although project organization and contract-related aspects have low direct performance impacts, they have influence on all other themes including Stakeholders' relationships and contract, Information sharing, documentation, and technologies, and Design and engineering planning, which have the highest direct performance impact. Thus, the earlier the project owners and designers aim for

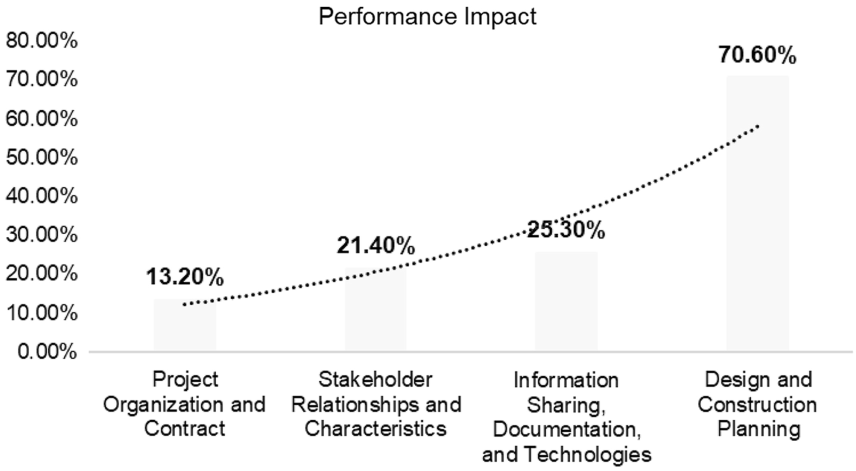

Fig. 5. Performance impact for each theme.

collaboration in the project, the higher the capitalization on the benefits of modular construction methods. Therefore, although the cascade size ratios show that early factors are important to promote collaborative working environment, the direct benefits of collaboration are captured during later stages of the project (i.e., design and construction planning phase).

Discussion of the Research Findings

Based on the research findings of this paper, the authors would provide a detailed discussion in relation to collaboration requirements in modular construction projects. Furthermore, the authors developed a graph in Fig. 6 depicting the different collaboration themes and their interdependence to achieve adequate collaborative environment. To this effect, the associated discussion will be based on the graph of Fig. 6 presented in the aforementioned subsection in relation to the four collaboration themes.

Project Organization and Contract

The Project organization and contract theme includes project delivery method selection, contract drafting and conditions, early involvement of contractors, subcontractors, and manufacturers, incentives, and efficient risk allocation. The selection of project delivery method is one of the collaboration factors that is not impacted by any other factors with an in-degree centrality equal to zero (Table S3). Such results align with those of Van der Ham and Opedenakker (2023), who considered project delivery selection as one of the earliest decisions establishing adequate collaboration among project stakeholders and thus impacting the success of every modular construction project. In fact, the adequate project delivery for modular construction is the one that (1) allows integration and alliancing among owners, designers, general contractors, and subcontractors/suppliers during the early phases of the project (Said 2015); and (2) affects the contractual terms and conditions stipulating the responsibilities of the parties in each project phase (Komurlu and Er 2020).

In addition to early involvement and contract drafting, the selection of an appropriate project delivery method is associated with various benefits including the ability to procure reliable expertise and project team members (Wuni and Shen 2020). Furthermore, the contract drafting resulting from the selected project delivery has a great influence to delineate the responsibilities of the stakeholders of modular construction projects as to ensure (1) efficient and fair risk allocation promoting trust and transparency among them; and (2) commitment and clear obligation for the stakeholders to collaborate in the project (Emuze and Smallwood 2014). Ultimately, the latter explains having the highest cascading effect of project organization on stakeholders' relationships and characteristics.

Table 13 clearly indicates that project organization and contract has the lowest direct impact on modular construction implementation, which is 13.2% growth in cost and time. However, the latter does not indicate that this theme does not have any impact on capturing the full benefits of modularization in construction projects. However, any failure in project organization and contract aspects have a cascading effect on all other aspects including Stakeholders' relationships and Information sharing, and design, and construction planning (Table 13). Thus, the establishment of effective collaboration environment in modular construction projects starts with adequate decisions in relation to project organization and contract.

Stakeholders' Relationships and Characteristics

The only aspects that affect this theme are those related to project organization and contract. Stakeholders' relationships and characteristics includes team workshops and training; prequalification and team selection; team skill, knowledge, and expertise; stakeholders' leadership and management support, commitment, and willingness for collaboration and cooperation; trust; and integration and alignment on project goals. Stakeholders' leadership and management support is one of the collaboration factors that is not impacted by any other factors with an in-degree centrality equal to zero (Table S3).

Such results align with the findings of Pablo and London (2020), who highlighted that the root of adequate collaboration in modular construction methods is associated with the availability of

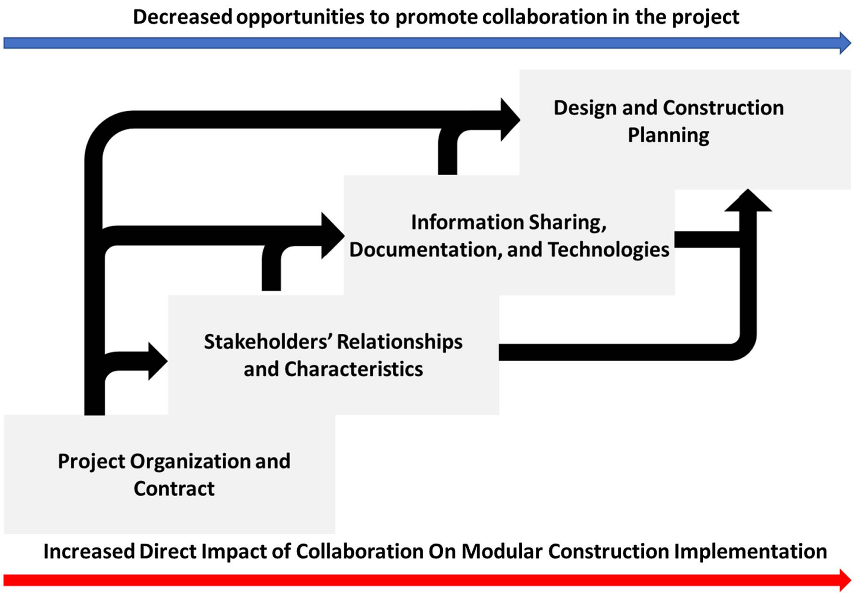

Fig. 6. Collaboration themes and their interdependence.

leadership characteristics in the industry's stakeholders. Ultimately, according to Emuze and Smallwood (2014), stakeholders' leadership and management support is an essential part to change current practices in relation to modular construction by creating team members who have common goals and objectives, and promoting trust. Ultimately, by ensuring alignment and trust among the project team members, project stakeholders will reflect even commitment to collaborate and cooperate during the project (Shafiee et al. 2020). In addition, efficient leaderships in project stakeholders, along with appropriate prequalification and team selection criteria, should ensure adequate workshops and training to ensure reliable expertise, skills, and knowledge of their team members (Wuni and Shen 2020).

Stakeholders' relationships and characteristics have significant impact on all collaboration aspects except for project organization and contract (Table 13). For instance, even commitment among the modular construction project stakeholders can ensure (1) efficient and frequent meetings (Dowsett et al. 2019), (2) adequate investment on interoperability in the project (Kim et al. 2017), and (3) easier integration of advanced technologies such as visualization tools and radio-frequency identification, among others (Rahimian et al. 2019). Ultimately, these results explain the high cascade size ratio of stakeholders' relationship and characteristics on information sharing, documentation, and technologies. Thus, stakeholders' relationships on the one hand and their experience and knowledge on the other are important to ensure adequate information sharing, documentation, and technologies as well as collaborative design and construction planning.

Information Sharing, Documentation, and Technologies

This theme is directly affected by project organization and contract as well as stakeholders' relationships and characteristics. Information sharing, documentation, and technologies includes investment on interoperability of adopted information technologies, integration of advanced technologies and visualization tools, building information modeling effectiveness, efficiency and frequency of meetings, effectiveness of communication and information sharing, and timely reporting and efficient trackability. Although it does not have any root factors, this theme is a crucial aspect of ensuring adequate collaboration the project, more particularly during the design and construction planning process. In fact, a good working collaborative work environment necessitates adequate information sharing among project stakeholders.

The success of modular construction projects depends on extensive and efficient information sharing and communication throughout the project life cycle including planning, design, and execution (Sun et al. 2020; Wuni et al. 2022). Furthermore, BIM is considered one of the main platforms used to generate digital representations that can be used for information sharing and exchange (Choi and Song 2014). However, the integration of other technologies such VR, AR, and GIS can further allow for easier communication of design and access to information (Rahimian et al. 2019).

Ultimately, all of the aforementioned factors have a direct impact on the collaboration level among project stakeholders during design and construction planning on the one hand, and on modular construction implementation phase on the other. More specifically, timely reporting and trackability during modular construction implementation have a great impact on activity sequencing and management, which is important to synchronize the work between off-site and onsite works as well as avoiding logistics-related risks onsite (Ezzeddine and de Soto 2021; Wuni et al. 2022; Lee and Lee 2021).

Design and Construction Planning

The results show that all the previous aspects have cascading effect on design and construction planning-related aspects. In fact, during design and construction planning, coordination should include (1) risk management, (2) constructability feedback, (3) lean construction practices, (4) efficiency and feasibility of design, (5) standardization, and (6) construction coordination. Thus, the results show that all collaboration aspects considered early in the project are exerted and reflected during the design and construction planning phase. The latter can also be reflected from the high in-degree centralities of the associated factors in Table S3. Although this is the most dependent theme, it has the highest direct impact on modular construction implementation (Table 13).

The results show that the various modular risks can be mitigated and avoided by ensuring collaboration during the design and construction planning phase. These modular risks include (1) inefficient assembly and installation equipment, (2) inefficient transportation planning, (3) inadequate site logistics, (4) rework, (5) inefficient material and waste management, (6) inadequate activity sequencing and management, (7) late design changes, (8) poor safety planning, (9) poor productivity, and (10) inadequate tolerance and interfacing. Therefore, the results show that design and planning constitute a bottleneck where related factors are highly sensitive to other collaboration factors on one the hand and have high direct impact on modular risks or modular construction implementation on the other.

Finally, inadequate coordination and collaboration in design and construction planning can lead up to 70.6% growth in schedule and cost of modularized projects. Despite being the highest influential aspect on project performance, design and planning command adequate early decisions in relation to project organization and contract as well as stakeholders' relationships and characteristics. Such early decisions can have a cascading impact on information sharing, documentation, and technologies as well as design and planning, leading to unsuccessful implementation of modular construction projects.

Theoretical and Practical Implications

This paper contributes to the body of knowledge by offering an unprecedented framework that investigates collaboration requirements in modular construction and their interdependencies. Theoretically, this paper is the first to ever investigate the impact of collaboration in an interdependent manner on the one hand and in relation to modular construction on the other. The impact of collaboration was investigated assuming a cascade effect to capture the direct and indirect effects of collaboration factors on the occurrence of modular risks impacting project performance. Thus, this paper contributes to the body of knowledge by investigating the early decisions that are needed to establish a strong collaborative working environment in modular construction projects. Another theoretical addition is the use of a modeling method that integrates network theory with Monte-Carlo simulation to investigate the cascade effect of collaboration on the performance of modular construction projects.

Regarding the practical implications, this paper provides practitioners with a list of factors impacting collaboration in modular construction projects. This paper also highlights the modular risks that are impacted by the level of collaboration in the project. Further, this study quantifies the direct impact of collaboration on the schedule and cost performance of modularized projects. The quantification of the direct impact of collaboration shows that the benefits are usually captured during the execution and planning phases, mainly in relation to design and construction. Despite the latter, the findings of this paper provides clear insights on the importance of early decision making for better establishment of collaborative working environment in the project and therefore adequate realization of collaboration benefits. Ultimately, based on the outcomes of this paper, the following recommendations were developed:

- In order to promote collaboration in the project, the stakeholders should focus on the following factors: effectiveness of communication and information sharing; team skill, knowledge, and expertise; contract drafting and conditions; early involvement of contractors, subcontractors, and manufacturers; efficiency and frequency of meetings; and building information modeling effectiveness.
- Some risks are more likely to occur in case of a lack of collaboration in modular construction projects. The modular risks with the highest failure probability include inadequate site logistics; late design changes; and inadequate tolerance and interfacing. The ones with the highest impact include late design changes; inadequate site logistics; and inefficient activity sequencing and management.
- The establishment of an effective collaboration environment in modular construction projects starts with adequate decisions in relation to project organization and contract. Any failure in project organization and contract aspects has a cascading effect on all other aspects including relationships and information sharing, design, and construction planning among the associated stakeholders.
- Stakeholders' relationships on the one hand and their experience and knowledge on the other hand are important to ensure adequate performance in relation to information sharing, documentation, and technologies as well as collaborative design and construction planning.
- Design and planning require adequate early decisions in relation to project organization and contract as well as stakeholders' relationships and characteristics. Such early decisions can have a cascading impact on information sharing, documentation, and technologies as well as design and planning, leading to unsuccessful implementation of modular construction projects.

Another practical implication is the development of a flexible collaboration network and cascade model. Such flexibility is associated with two main aspects. The first aspect is on the project level with different characteristics such as level of modularization, project sector, experience in collaboration, and stakeholders' characteristics. The second aspect is associated with the abstract level of the network. In other words, the developed network and cascade model can be used as a base model to further increase the level of details on one hand and add further factors that may affect collaboration but were not included in this study.

Conclusion, Limitations, and Future Research Work

This paper investigated collaboration requirements in modular construction projects and their cascade failure effect on project. First, the authors identified a list of collaboration factors, impacted modular risks, and their cause–effect relationships using systematic literature review analysis. Second, the most influential and sensitive factors in relation to collaboration were identified using network analysis. Third, cascade modeling was performed to capture the interdependency among various collaboration themes and their impact on project performance. Ultimately, the authors identified a total of 25 collaboration factors categorized under four different themes, including Project organization and contract, Stakeholders' relationships and characteristics, Information sharing, documentation, and technologies, and Design and construction planning.

Furthermore, a list of 10 modular construction operation risks were found to be highly impacted by the level of collaboration in the project. Although the most influential factors were related to information sharing, documentation, and technologies, the most sensitive factors fell within the design and construction planning. Ultimately, the outcomes show that inadequate collaboration during design and construction planning can lead to 70.6% direct growth in schedule and cost of modularized projects. Despite being the highest influential aspect on project performance, efficient design and construction planning requires adequate early decisions in relation to project organization and contract as well as stakeholder relationships and characteristics, which influence information sharing, documentation, and technologies as well as design and planning leading to unsuccessful implementation of modular construction projects.

This paper contributes to the body of knowledge by offering an unprecedented framework that investigates collaboration requirements in modular construction in an interdependent manner. Ultimately, the findings of this paper provide clear insights on the importance of early decision making for better establishment of collaborative working environment in the project. Further, this study quantifies the direct impact of collaboration on the schedule and cost performance of modularized projects.

One of the limitations of this study is that not all respondents of the collaboration survey possessed experience in modularization. However, this was somewhat expected and perhaps unavoidable because not only are collaborative project delivery methods still adopted at relatively low rates, but also the modular construction market is considered to be really small. This was accounted for by the extensive expertise of the respondents both in the construction industry as well as collaborative planning practices to ensure effective and efficient applicability to modular construction. However, all other data, including collaboration factors, modular risks, their direct causal relationships, risk probability, and impact, reflect the characteristics of modularization.

Another potential limitation associated with this study is the absence of factors that may affect collaboration in modular construction projects but were not included in the network. However, the authors aimed to avoid this potential limitation by identifying the collaboration factors based on a comprehensive investigation of the literature. Another limitation is that the probabilities, impacts, and importance of collaboration factors may differ from one project to the other based on the level of modularization adopted and experience of stakeholders in collaborative work environment, among others. However, the developed model is flexible and can be adjusted by changing the probabilities, impact, and importance so as to align with the characteristics of specific projects and stakeholders' requirements.

Inspired by the discussion and findings of this paper, future research studies can further (1) analyze feasibility of modular construction in terms of the suitability of various project delivery methods, (2) investigate information flow required among the various parties during the various project phases of modular construction, (3) provide recommended changes in the terms and conditions of current standard forms of contract to accommodate for the complex requirements of modular construction methods, and (4) use the developed network as a base model to further expand the network in terms of the incorporated collaboration factors and level of details.

Data Availability Statement

All data, models, and code generated or used during the study appear in the published article.

Supplemental Materials

Tables S1–S5 and Fig. S1 are available online in the ASCE Library (www.ascelibrary.org).

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