Journal of Civil Engineering and Management
ISSN 1392-3730 / eISSN 1822-3605
2023 Volume 29 Issue 5: 418–438
https://doi.org/10.3846/jcem.2023.18868

INFLUENCE OF COLLABORATIVE RELATIONSHIPS ON THE PERFORMANCE OF DESIGN-CONSTRUCTION EFFICIENCY OF INDUSTRIALIZED CONSTRUCTION

Yidnekachew Tesmamma DAGET*, Hong ZHANG#

School of Architecture, Southeast University, Nanjing, China

Received 18 August 2019; accepted 30 January 2023

Abstract. The poor collaboration among the main actors in the construction has become a challenge for the low performance of the design-construction efficiency (DCE). This study investigated and quantitatively evaluated the influence of network relationships in stakeholders' collaborative management (SCM) and their effect on the performance of the DCE of industrialized construction projects. Hypotheses were proposed and tested. Based on multiple empirical cases, semi-structured interviews and questionnaire surveys were conducted. Social network analysis (SNA) was adopted as a research technique for graphical analysis and quantitative evaluation of the SCM. The study's findings revealed that the different sets and modes of collaboration directly impacted the performance of the DCE of industrialized construction. Further findings showed that strong collaboration among the contractors, designers, and manufacturers significantly impacts achieving better efficiency. Meanwhile, DCE was the most important driving factor for the SCM. The network relationships had a positive impact on the DCE. The study contributes knowledge in demonstrating the application of network relationships in industrialized construction research and helps practitioners establish a strong SCM to improve the efficiency of industrialized construction in a wider global context.

Keywords: Design-construction efficiency (DCE), network relationships, stakeholders' collaborative management (SCM), social network analysis (SNA), industrialized construction, industrialized house building.

Online supplementary material: Supporting information for this paper is available as online supplementary material at https://doi.org/10.3846/jcem.2023.18868

Introduction

The construction industry has been one of the most inefficient and lagging behind other advanced manufacturing industries in terms of performance and efficiency (Costa et al., 2019; Murtazova & Aliev, 2021; Shehu et al., 2014). However, the construction industry has shown a 1% average annual growth in the last two decades, representing a quarter of manufacturing sector growth and a third of global economic growth (Hossain & Nadeem, 2019). Nevertheless, time and cost overrun have been challenges to construction projects. In addition, the construction market requires products of high quality at low prices. These limitations are worsened by the growing lack of skilled construction labor, increasing labor costs, and reducing construction quality and efficiency (Murtazova & Aliev, 2021). Furthermore, industry fragmentation, complicated building standards, and low levels of investment in technology, research, and digitalization contribute to lower construction productivity (Mellado & Lou, 2020).

An industrialized construction strategy is one of the solutions to the historical failure and inefficiency of the construction industry (Kedir & Hall, 2021). Prefabricated building component methods are central to industrialized construction (Lessing, 2006). This method helps construction companies to make more profit and prove its efficiency to those practitioners who applied the technique early in their projects (Wu et al., 2021). The industrialized house-building is one part of industrialized construction focusing on residential housing projects (Jansson, 2017; Lessing, 2006). New industrialized house practices are emerging in the construction industry to address a broad set of productivity issues that cut across strategic domains, technological, and organizational structure. Offsite con-

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*Corresponding author. E-mail: *tesmammay@yahoo.com*
#Corresponding author. E-mail: *zhangh555@aliyun.com*

struction yet faces various challenges despite all its economic and sustainable benefits (Kedir & Hall, 2021). In several countries, there are difficulties in industrialized house-building projects due to poor communication, discontinuity, fragmentation, and silo thinking of stakeholders (Nawi et al., 2014). The fragmentation and poor communication in industrialized house-building projects widen the gap between the stakeholders' collaboration to achieve improved performance of the design-construction efficiency (DCE) (Eriksson et al., 2009; Lu et al., 2020).

One of the most realistic options for overcoming the crisis in the construction industry is to develop strong collaborative relationships among stakeholders (Murtazova & Aliev, 2021). The fact that a project is comprised of many stakeholders from various professional organizations requires effective and efficient communication, coordination, and cooperation to deliver the project value (Mignone et al., 2016; Oraee et al., 2017; Soderlund, 2011). The stakeholders are the actors involved in the design-construction work of a building project, such as architects (designers), contractors, clients, component manufacturers, suppliers, and supervisors (Xue et al., 2018a). All stakeholders in a given project are not equally involved in the entire project life cycle (Xue et al., 2018b). As such, they do not always work together efficiently and can have competing interests. The network relationships among the stakeholders determine the nature of collaboration and directly impact the efficiency of the project execution of industrialized house construction (Kishna et al., 2017; Safford et al., 2009).

Practitioners, researchers, and societies are giving increasing consideration to improving project performance. They explored responding strategies such as rethinking project management (Li et al., 2009), encouraging communication (Murray et al., 2007), promoting relational contracting, as well as accentuating the value of trust and culture (Pryke et al., 2017). Advocating effective stakeholder collaborative management (SCM) and network relationships gained prominence. They helped integrate industrialized buildings' design, supply chain, production, and installation process (Jiang et al., 2018; Vibaek, 2014; Xue, 2011; Xue et al., 2018a). Optimizing collaborative relationships can prompt construction efficiency (Xue et al., 2018b). Prior studies have systematically investigated the SCM relating to innovation, cost management, and manufacturers (Kishna et al., 2017; Xue et al., 2018a, 2018b; Yang et al., 2009). However, there is a knowledge gap in quantitatively evaluating the effect of stakeholders' collaboration on the DCE, and little has been empirically verified. In addition, the key actors that significantly improve the performance of DCE of industrialized housing construction are hardly covered in the literature. This study focuses on the quantitative evaluation of stakeholders' collaboration to identify the impact of the main actors involved on the overall efficiency of the DCE. The study contributes knowledge in demonstrating the application of network relationships in industrialized construction research and helps practitioners establish a strong SCM to improve the efficiency of industrialized construction in a wider global context.

This paper has the following main objectives:

- To examine and understand the influence of network relationships and quantitatively evaluates the effects of SCM on the performance of DCE of industrialized house build construction projects.
- To evaluate each actor's influence in the network relationships and identify the influential actor/s for the efficiency of industrialized house-building projects.

The study conducted and applied the social network analyses (SNAs) research technique. Based on the research objective, the following are the main research questions: First, how do the network relationships among the key stakeholders on the SCM affect the project's DCE performance? Second, how can the weights of each actor's influence level in the network relationships among the stakeholders be evaluated? The research questions take the theoretical stance that projects are social networks. Turning projects into network relationships also allows SNA as a study technique, particularly its sociological and mathematical approaches, to study project relationships in a manner that will inspire academic and practical interests (Hughes et al., 2002). It is suggested that using SCM will change a project and its associated social network by encouraging collaboration, coordination, and facilitating communication, thereby increasing project performance. The research particularly benefited from the suitable datasets from four industrialized housing projects. The datasets are used to analyze their network relationships and their DCE performance.

1. Literature review

1.1. Design-construction efficiency (DCE)

Design-construction efficiency (DCE) is the measure of the performance of a project team in exhausting all techniques and methodologies to optimize the design and construction process. It includes the use of optimum material and components as well as the relations among the project members to provide maximum capacity at minimum cost (Adu & Opawole, 2020; Indriani et al., 2020; Kedir & Hall, 2021; Nawi et al., 2014; Yap et al., 2020).

Problems associated with fragmentation in the traditional construction process, such as lack of effective teams between design and construction, the sequential manner of its operations, and isolation of experts, have impacted construction performance leading to wastage, a lack of integration, low productivity, and inefficiency (Kent & Becerik-Gerber, 2010; Nawi et al., 2014). On the other hand, industrialized building construction improves labor productivity through standardized design, factory production of structural components, and on-site assembly construction (Wu et al., 2021). As a result, it has become a key strategic direction for the construction industry to upgrade traditional buildings and has attracted significant industry attention (Wang et al., 2016).

DCE is emerging as a representation of efficiency where professionals can better communicate with each other for better performance in design and construction (Adu & Opawole, 2020; Salleh et al., 2019; Yap et al., 2020). Pan (2007) discussed that the improved performance of DCE benefited the promotion of prefab expertise. However, DCE takes the effort of all the project's primary stakeholders, such as the client/owner, designer, contractor, manufacturers, supervisor, specialized sub-contractors, and supplier (Xue et al., 2018b). If continuous improvement in DCE is to be achieved through the use of SCM in the construction, then there needs to be a system or means of measuring how well-integrated a team is (Baiden et al., 2006; Xue et al., 2018a). Research regarding SCM in industrialized construction helps improve the construction's performance efficiency (Xue et al., 2018a, 2018b; Yap et al., 2020). This study quantitatively evaluates and analyzes the effect of the network relationships on SCM to understand the possible practical way to achieve DCE in industrialized construction. The leading measurable indicators that are used to discuss the performance of DCE in industrialized housing projects are integrated design, integrated construction, construction schedule, and integrated management (Ismail et al., 2012; Jiang et al., 2018; Singh et al., 2015; Vibaek, 2014).

These measurable indicators have been suggested to address the inefficiency of fragmented product delivery processes by breaking down barriers to effective collaborative working (Baiden et al., 2006). Integrated design involves a thorough planning strategy to manage the technical and process performances (Lessing et al., 2005). It often uses a product-based approach contrary to the project-based approach found in the traditional construction industry. This product-based approach allows stakeholders to create a shared understanding of the product at the early stages of the construction process (Kedir & Hall, 2021; Tykkä et al., 2010). Integrated construction is considered a complex network involving multiple interactions and collaboration among actors during construction (Fellows & Liu, 2012; Winch, 2001). Efficient construction integrates actors for better information sharing, improving cooperation and trust (Le et al., 2021; Thunberg & Fredriksson, 2018). Integrated management is the key to establishing transparent contractual relationships, well-established project goals, and team confirmation from the beginning, which are essential for DCE success (Mellado & Lou, 2020). Other factors for DCE success are well-defined roles, a clear scope of work, responsibilities, and relationships (Kent & Becerik-Gerber, 2010). Therefore, it is seen that successful integration processes are under integrated management. The construction schedule is project planning and optimization of adequate allocation of resources, equipment, and labor to control better the construction process (Abbasi et al., 2020; Xie et al., 2020). The construction schedule will also help to avoid increased time, cost, and waste (Liao et al., 2014).

1.2. Network relationships

Consider projects as network relationships will not only help to understand the uncertainties and dynamics of governance and resource management in projects but also delivers a theoretical connection to adopting SNA as the kernel of the methodology of this paper. The projects' network view is not mutually exclusive with other prevalent projects' view, e.g., as a system for information flows management (Winch, 1989); as a form of temporary organization (Turner & Muller, 2003); or as a set of informal and formal institutions imprinting and regulatory actions (Wang et al., 2018).

Previous studies investigate project organizations related to theories and analysis of project network relationships, which consist of actors and their inter-relationships (Chinowsky et al., 2010). Three essential norms fundamental to the popularization of network relationships theories and analyses to ease the understanding of project organizations are (1) all human activities are the result of human relationships; (2) within a given network, actors are a function of that environment by contributing to the environment; and (3) unless considering the whole networks, it is not easy to understand the project and their nature of the relationships (Pryke et al., 2017). Investigating a project from the viewpoint of network relationships means explaining project phenomena by observing relationships between processes, resources, and stakeholders (Steen et al., 2018). It tests the position of actors and the established relationships between different stakeholders through network metrics.

Construction projects as network relationships have also been studied by scholars, some from an overall project background, while others are from specific construction. Noharia and Eccles (1992) stated that all organizations are social networks and therefore need to be studied in terms of networks of relationships. Pryke (2012) proposed that a construction project can be signified as a multilayer of mutually dependent networks. In these works, construction projects are theorized as a provisional network embedded with a fixed time cycle and particular purposes brought by groups of actors engaging in multifaceted problem-solving procedures and cooperating through informal and formal relationships (Pryke et al., 2017). Based on the scholarly works, it is legitimate to view a construction project as a social network and to examine the impact of the network relationships of SCM on the performance of the DCE of the project.

The industrialized construction project implementation process takes place in a complex, non-linear, iterative, and collaborative environment in which the influence of network relationships has tremendous significance for collaboration among the key actors (Sánchez, 2015; Shen et al., 2010). During the project development, a decision change made by any stakeholders or their respective poor performance of expected duty directly impacts the project's incremental progress. Therefore, the main actors in the project need to establish strong collaboration. Previous studies discussed the significance of network relationships among stakeholders based on information exchange (Bamgbade et al., 2017; Mustapha et al., 2017). Although the level of the network relationships among stakeholders for the performance of the DCE is not yet quantitatively evaluated, studies set the attributes used for measurement of the network relationships are density, degree centrality, and betweenness centrality (Pemsel & Wiewiora, 2013; Sun & Zhang, 2011). Density signifies the level of closeness and can be used to regulate the connections among the stakeholders. The degree of centrality is the evaluation of the node positions and indicates the importance of each stakeholder in the network relationships (Golob et al., 2013; Jalal & Koosha, 2015). The betweenness centrality shows the degree of control or brokering advantage a specific actor (node) can have over the communication flow. Finally, the closeness centrality represents the extent of information flow and the inter-dependence among the main actors in the network relationships (Chapman & Corso, 2005; Golob et al., 2013).

1.3. Stakeholder collaborative management (SCM)

The high complexity and uncertainty of significant construction projects call for a rigorous approach to managing the relationships and conflicting needs of stakeholders who play a pivotal role in project success (Mok & Shen, 2016). A project environment can be perceived as a network system composed of interconnected stakeholders and interrelated stakeholder issues. The characteristics of and propagating effects produced by these network structures are affected by stakeholders' perceptions, salience, and impacts (Chinowsky et al., 2008). According to Wasserman and Faust (1994), the performance and robustness of a network system are readily affected by the interconnected elements within this system and the ways that these elements are linked together. In addition, previous studies revealed that SCM could depict the network relationship. SCM affects a temporary or permanent network relationship by coordinating and strengthening information exchange, communication efficiency, and resource sharing for better project performance (Xue et al., 2018b). The interaction of solid network relationships depends on the realization of SCM, and the benefits of SCM are derived from the position of the stakeholders in the network relationships (Xue et al., 2018a). The roles of each stakeholder have degrees of impact on the status of the network relationships.

SCM is considered an inter-organizational cooperative and social network for effective project administration in industrialized construction projects (Antoncic & Prodan, 2008; Xue et al., 2018a, 2018b). SCM also plays a vital role in altering interdisciplinary collaboration in project management. A fundamental principle of SCM is to assist communication among professionals at various stages of the project life cycle to manage information and support the stakeholders' responsibilities. Conventionally, clients, designers, administrative organizations, and contractors are largely isolated; their communication is relatively constrained by physical distance, knowledge gap, and time. SCM is promoted as an easing method, principally working with integrated project delivery, to offer opportunities for broader collaborations. SCM can offer the advantages of (1) allowing simultaneous communication compared with serial workflows of information generation and examination; (2) integrating distinct tasks, including spatial coordination, scheduling, and estimating more effectively; and (3) improving distinct tasks (Becerik-Gerber et al., 2012).

Previous studies discussed that the SCM affects overall project performance in industrialized housing construction projects regarding the time, budget, and quality objectives (Rutten et al., 2009; Xue et al., 2018a). De Marco et al. (2015) argued that organized collaboration significantly influences the financial process's decision-making. Similarly, Xue et al. (2018b) revealed that SCM positively affects cost performance in industrialized construction. Jalal and Koosha (2015) discussed that good coordination improves the construction process. Winch (2003) also showed that the key actors need to establish a shared goal for strong collaboration; Golob et al. (2013) revealed that the shared goal of the main actors had a significant role in improving project performance and completion time. Finally, Xue et al. (2018a) discussed that strong SCM promotes the development of innovative industrialized housing construction methods; The quality of the interaction is influenced by the rate of communication among the main actors (Chapman & Corso, 2005).

The quantitative evaluation of SCM can be done through measurable indicating factors, such as communication frequency (Chapman & Corso, 2005), emotional intensity (Jalal & Koosha, 2015), familiarity (Antoncic & Prodan, 2008), and exchange of information and technology (Golob et al., 2013). Communication frequency denotes the intensity and rate of interaction or the frequency of communication time among the main actors. Emotional connection is the contractual relationship and depth of emotional intensity among the participants. Familiarity represents participants' degree of understanding and familiarity and the duration of group working time. Finally, the exchange of information and technology signifies the scale and reciprocity of sharing data, skills, and technologies for the shared benefit of all participants.

1.4. Stakeholder's collaboration theory

Since Freeman (1984) published his seminal book, *Strategic Management: A Stakeholder Approach*, much work has been done to develop stakeholder theory. As Donaldson and Preston (1995) summarize, there are three primary streams of research within the stakeholder tradition: instrumental, normative, and descriptive. Instrumental stakeholder research focuses on how firms pursue their interests through managing relationships with stakeholder groups. Normative stakeholder theory focuses on the moral obligations of managers concerning their stakeholders.

Finally, descriptive stakeholder theory describes the actual behavior of managers, firms, and stakeholders. Of these, this study will focus on instrumental stakeholder perspectives where an organization establishes stakeholder network relationships to achieve a better performance of DCE.

Stakeholders include any person, group, or organization that affects and impact an organization's decisions (Freeman, 1984). Given various types of organization–stakeholder relationships, researchers have identified strategies for managing stakeholders from the focal organization's viewpoint (Savage et al., 1991). However, theories that examine stakeholder network relationships (Rowley, 1997; Rowley & Moldoveanu, 2003) seem most relevant for social partnerships. A network perspective goes beyond simply examining dyadic firm–stakeholder relationships and focuses on how the nexus of stakeholder relationships affects social collaboration. On the one hand, Rowley (1997) argues that the structure of relationships among and between stakeholders influences the actions of a focal organization. On the other hand, from a social partnership perspective, the network of stakeholder relationships determines whether one stakeholder may dominate the partnership. The level of interest symmetry and identity overlap among the network of stakeholders may influence whether the social partnership is supported or opposed.

In construction projects, stakeholders are connected directly or indirectly by network relationships across functional and organizational borders, so they are embedded in various social networks instead of being isolated in a vacuum (Chinowsky et al., 2008). Therefore, the relationships and interactions of stakeholders are significant factors determining stakeholders' behaviors and impacts on the performance of DCE.

1.5. Summary and hypothesis

Studies on the DCE, network relationships, and SCM are scattered across various studies. However, the studies showed that network relationships and SCM of the main actors involved in the design and construction directly impact the performance of the DCE of industrialized buildings. In addition, measuring factors can be applied to quantitatively evaluate the DCE, network relationships, and stakeholders' collaborations. Furthermore, as of the instrumental stakeholder theory, establishing organizational structures for stakeholders' network relationships helps to improve the performance of DCE. However, a few papers focus on issues related to the industrialized building (Hu et al., 2019; Nguyen et al., 2021; Teng et al., 2017; Xue et al., 2018b). Still, a comprehensive review does not yet exist regarding the intersection of DCE, network relationships, and SCM with an industrialized building.

This study contributes to knowledge in demonstrating the application of network relationships in industrialized construction research and helps practitioners to establish a solid SCM to improve the efficiency of industrialized construction in a broader global context. Accordingly, a systematic method is needed to examine and evaluate the interactions of stakeholders and their roles in the network relationships (Mok & Shen, 2016). Based on the above discussions on the necessity of having structures and relationship ties to build collaboration with a focal organization objective, this study proposes a collaboration study model as instrumental theory (see Figure 1). A focal aim is to analyze and quantitatively evaluate the effect of the stakeholders' network relationships and their SCM on the overall performance of the DCE of industrializing house buildings. The study model is graphically presented

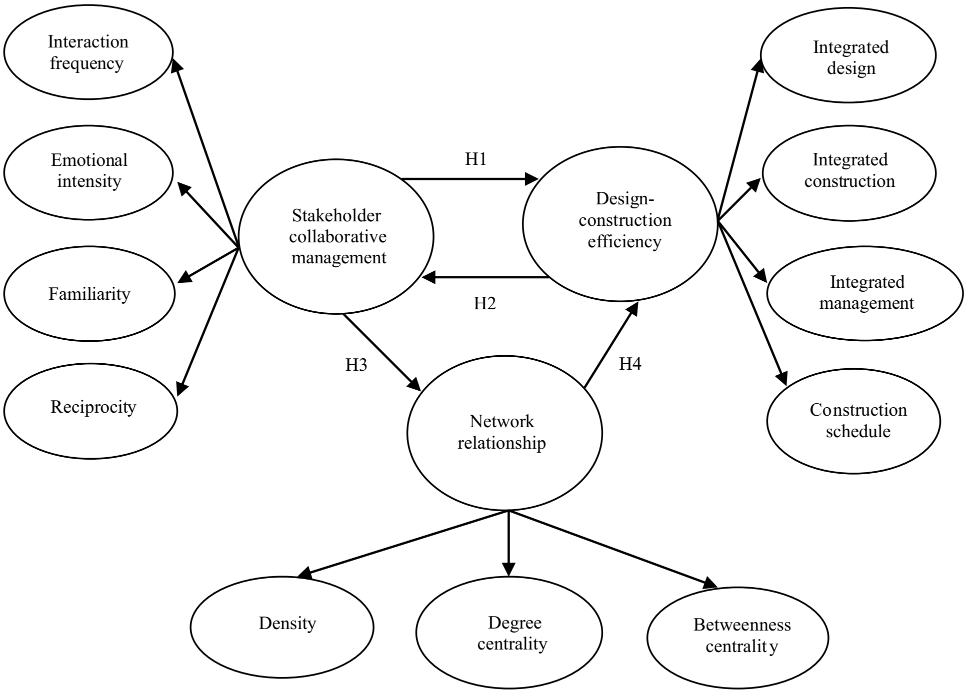


Figure 1. The collaboration study model

to visualize the inter-relationships of the three main parts of the study (i.e., network relationships, SCM, and DCE) alongside their measuring factors for further quantitative investigation based on the proposed hypothesis listed below.

H1. SCM positively influences the performance of DCE.

H2. DCE positively influences SCM.

H3. SCM positively influences network relationships.

H4. Network relationships positively influence DCE.

2. Methodology

2.1. Research methods and techniques

This study sought to understand and quantitatively evaluate the effect of the level of the network relationships in the SCM for the overall performance of the DCE. In addition, it evaluates the level of influence of each actor in the network relationships and identifies the influential actor/s for the efficiency of industrialized house-building projects. Based on the objectives of the study, mixed methodologies of both qualitative and survey-based quantitative research methods were applied (see Figure 2) (Almalki, 2016). A relevant literature review was conducted to understand the network relationships of SCM and their impact on the DCE. Then, measuring factors were identified from the literature for the evaluation of DCE, network relationships, and SCM. Simultaneously, four industrialized house buildings from Ethiopia and China were investigated as empirical cases (see Table 1) (Yin, 2009). The cases were selected among similar projects based on their application of industrialized housing systems to promote the efficiency of the construction (Supplemental File 1). The cases were reviewed and evaluated to understand the influences and interactions among network relationships, SCM, and DCE of industrialized construction projects. The on-site project investigation was executed over the last two years. In the meantime, project documents were studied to enable thorough understandings and direct observations. The projects were implemented at different times and in a different context which made them describe a different scenario in the SCM. Attention was also given to contextual differences to minimize the possible effects. Both qualitative and quantitative data were collected through field interviews, questionnaire surveys, and direct literature surveys. Interviews with project participants were undertaken to draw a lesson from their insights regarding the SCM. In addition, the survey data conducted with the 28 professionals (see Supplemental File 2) were gathered and examined. The professionals are experts engaged in industrialized construction project teamwork with an average of more than 15 years of experience. The study has limitations regarding the number of survey respondents due to the lack of the availability of a sufficient number of experts engaged in industrialized construction. However, the study has made an in-depth investigation to capture richly-textured information relevant to the study theme under investigation (Jw, 1998). The experts are invited to make suggestions on the performance of DCE of SCM based on the proposed collaboration study model (see Figure 1). Lastly, the stakeholders' network relationships and their respective features were evaluated based on a social network analysis (SNA) method and also using UCINET6.0 analysis software. UCINET software tool is employed because it is a widely used technique for quantitative analysis of network relationships (Borgatti et al., 2002; Xue et al., 2018a). Lessons drawn from the analysis are summarized and put into the findings and conclusions sections of this study.

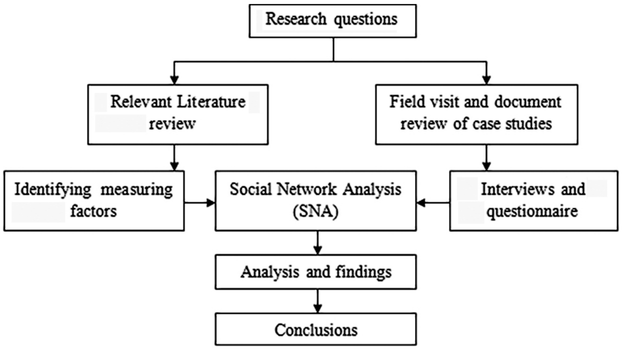


Figure 2. Research flow diagram

The main research technique applied in this study, i.e., the social network analysis (SNA) is the technique that has been widely applied to identify and evaluate the network relationships between the SCM (Mok et al., 2015; Xue et al., 2018b; Yang et al., 2011). The graphical representation and social network metrics are the tools used in the SNA method. The main actors and their inter-relationship made the social network. The main actors or the stakeholders are represented by a node in the social network graph while their relationship is represented by a node-connecting line which is called a tie. SNA examines the attributes of the nodes concerning their position and also their degree of ties in the social network. The position of nodes and the degree of the strength of their relationships are evaluated based on the measure of density and centrality (Gilsing & Nooteboom, 2006). The level of closeness between nodes is signified by density (Park et al., 2011). The more the nodes are close to each other the higher will be the value of the density and the better will be the exchange of information and sharing of resources. The importance level of the nodes which suggests the influential power of the node over the other actors is measured by the value of centrality. The more important the role of a node is the higher will be its centrality value (Todo et al., 2016). Changing the spot of nodes has either a negative or positive impact on the stakeholders' behavior. The main stakeholders can make a continuous adjustment and a dynamic change in the position and power of a node in a network to make a situation suitable for the particular project. Therefore, the SNA was used in this paper to portray and evaluate the network relationships among the SCM.

2.2. Discussion of validity

Validity in research means the "appropriateness" of the tools, processes, and data (Leung, 2015). Various data sources were used to secure validity and reliability based on an organized study plan. Reliability was supported by interviewing the same individuals on different occasions. To understand the insights of the project participants about the SCM, several repeated interviews were undertaken. To secure validity (Yin, 2003), the study was conducted based on a proposed collaborative study model using appropriate methodology, sampling, and data analysis (Kreiter & Zaidi, 2020). The model also contributes to achieving internal validity in explaining diverse cases of the network relationships among the SCM of each project.

Regarding external validity or generalization, case study investigation requires caution. However, evaluation of the influence of SCM on the performance of DCE of industrialized house construction can stand the test of generalization (Lessing & Brege, 2018) and can be applicable to several countries. Generalizations about variances between Ethiopia and the China have to be avoided entirely, except for the dissimilarities in development prospects.

2.3. Case studies

2.3.1. Apt 16 (Case A)

Apt 16 is one of the first series of prefabricated residential building projects in Addis Ababa. The project applied the IMS pre-stressed concrete structural system for speedy construction to achieve a high rate of housing provision. The Ethiopian building and Transport Construction Design Authority conducted the design of the buildings. The Ethiopian Prefabricated Building Parts Enterprise did the production, supervision, and installation of the prefabricated components of the building. The building has two discrete assembly phases based on the construction work delivery mode. The first part is the foundation and structural parts assembly phase which took only six months to complete. In contrast, the second part took over seven years of overextended time. This extended time is due to not only the delivery system mode but also mainly the lack of finance, material availability, concurrent onsite construction management, political instability, and regime change within the country.

2.3.2. Special housing (CMC) (Case B)

The project is situated in an area of approximately 22 hectares and is distributed among 56 buildings of varying architectural styles. Five hundred apartment units for diplomats and higher government officials and various shops and service buildings were constructed. As the owner of the project, the Ministry of Urban Development and Housing of Ethiopia had selected the important actors who participated in a different role in the project. The construction work of the five hundred apartments was assigned to Cooperativa Muratorie Cementisti C.M.C of Ravenna (Italy). The design and supervision were commissioned to Foster Wheeler Italiana of Milan (Italy) in collaboration with the Ethiopian Building and Transport Construction Design Authority as a contract management consultant. As a (turnkey) contract, CMC is focused on the execution and construction phases or stages of a building project. Project design and design development are mostly limited to the technical engineering disciplines and are based on the proposed layouts of the design consultant following the production capacity of the prefab manufacturing industry established by the contractor.

2.3.3. Yi Hui Tang project (Case C)

This project is a new type of building industrialization demonstration project. It has two floors with a total construction area of 350 m^2. The construction of the building was completed and put into use within three months. The component classification of the design method contributes to smoother collaboration among the stakeholders with a clear objective and better communication. The collaboration helps to achieve effective construction management and improves the quality and duration of the project completion. The overall building is divided into two major categories, i.e., structural body groups and other component body groups. The structural body groups of the building were further divided into different categories, such as the primary structural body, the extended structural body, the basic enclosure body, and the extended enclosure body. Each component body group was designed and developed separately on which it was suitable for professional manufacturers to collaborate from the initial stage of the design development.

The construction process was organized around a relatively large amount of individual trade contracts directly between the client, Changzhou Institute of Building Science, and the different contractors. The project-specific splits of responsibilities were established during the design development stage. This form of integrated component-based design, production, and installation is called collaborative construction management. The individual contracts are called trade contract packages or simply: work packages. The work interfaces of the collaborative design were divided into parts to avoid problems in the relationship and connection between the components. The work interfaces also give all the participants enhanced control over the specific division into contracts.

2.3.4. Dreamhouse project (Case D)

Dreamhouse was a practical exploration of collaborative design and integration of building systems. This collaboration ensured the smooth and efficient implementation of the dream-house demonstration project. The project aim was to achieve energy-plus self-sufficient green buildings. It also applied advanced industrialized house building design and construction efficiency. The project involved four significant steps. First, the overall building layouts were categorized into component classification and modular groups. Second, enterprises for each modular group design and production were selected. Third, a collaborative design was developed and followed by the manufacturing of components. Finally, the space modules were assembled in the factory and transported to the building site to install the whole housing system. 95% of the project is completed in the factory, and the space modules are bolted to facilitate disassembly and reconstruction. The entire assembly process was straightforward and orderly, and it took only two weeks to complete the construction process.

2.4. Identifying the SCM measurable factors and framework

The attributes of SCM derived from the literature review were selected as measurable indicators for analysis. They are communication frequency, emotional connection, familiarity, and exchange of information and technology (see Table 2). Then, the selected factors are further tested through semi-structured interviews. A total of 10 well-experienced industrialized construction experts were

Table 1. Summary of the case study projects description

Projects	Apt 16 (Case A)	Special housing project (Case B)
Types	Apartment building	500 Apartment building s
Location	Addis Ababa, Ethiopia	Addis Ababa, Ethiopia
Building area (m2)	450	22 hectares
Structure system	Pre-stressed concrete	Architectural precast concrete
Height (m)	30 m	Different types
No. of stories	9	Range from 2 stories up to 5 stories
Precast level (% by volume)	65%	90%
Type of prefab components	Pre-stressed concrete slab, column, beam, wall stair	Precast wall, floor, column, beam, stair, prefab bathroom, and kitchen modules
Project completion time	1-year structure	2 years
Projects	Yi Hui Tang (Case C)	Dreamhouse (Case D)
Types	Residential building	Residential house (Flexible for emergency use)
Location	Changzhou, China	Changzhou, China
Building area (m2)	350	420
Structure system	Concrete-steel	Steel
Height (m)	16	12
No. of stories	3	1
Precast level (% by volume)	80%	95%
Type of prefab components	Precast concrete, prefab high-tech wallboards, steel component, solar room,	Steel modular structure, modular furniture, solar panel,
Project completion time	Three months	Two weeks

Table 2. The interview guage

Indicators	Definition	Evaluation factor	Data sources	Evaluation criterion
Communication frequency	Interaction between two stakeholders per unit of time	Intensity and rate of interaction	Chapman and Corso (2005), Antoncic and Prodan (2008), Xue et al. (2018a)	5 – Frequently (1–2 times a week), 4 – Sometimes (1–2 times a month), 3 – Occasionally (1–2 times a half-year), 2 – Hardly (except when accidents or specific events occur), 1 – Never
Emotional connection	Depth of emotional intensity among participants	Contractual relationship	Jalal and Koosha (2015), Xue et al. (2018a, 2018b)	5 – Contractual relation, 4 – Instruction relation, 3 – Coordination relation, 2 – Information exchange relation, 1 – Not direct relation
Familiarity	Degree of understanding and familiarity among participants	Length of time to work together	Antoncic and Prodan (2008), Rutten et al. (2009), Xue et al. (2018b)	5–80 – 100%, 4–60 – 80%, 3–40 – 60%, 2–20 – 24%, 1–0 – 20%
Exchange of information and technology	Reciprocity of information technologies shared the benefit of participants	Depth of exchange of technologies, resources, and information	Golob et al. (2013), Xue et al. (2018a)	5 – Must, 4 – Should, 3 – Can, 2 – Maybe, 1 – No

interviewed (see Supplemental File 3). A 30–40 min interview was held with the ten experts, including two contractors, two designers, one client, two professors, one subcontractor, and two precast concrete manufacturers. The interviews examined evaluation indicators and their contextual description (see Supplemental File 4). The professionals' opinions justified the validity of the selected measurable factors. In the meantime, data was also collected regarding the network relationships among the SCM. The main stakeholders (actors) selected for investigation were selected based on the previous studies (Hu et al., 2019; Teng et al., 2017; Xue et al., 2018b). In practice, their concerns and expectations must be identified, assessed, and balanced, given their profound impacts on project performance (Olander & Landin, 2005). The stakeholder concepts of Freeman (1984) and the Project Management Institute (2013) defined stakeholders as any individuals, groups, or organizations who can affect, be affected by, or perceive themselves to be affected by the achievement of the project's objective. Industrialized construction's stakeholders include but are not limited to, manufacturers, suppliers, supervisors, designers, contractors, clients, and specialty contractors.

2.5. Data collection and analysis of SCM and network relationship

The data for the two cases were collected from Ethiopian industrialized housing development projects, and the other two were from China, Changzhou city greenhouse demonstration industrialized housing projects. The data collection procedure's first step was preparing the guideline for interview measurement (see Table 2). Second, professionals with expertise in industrialized construction were selected. Third, the interview was undertaken. Fourth, the collected data was summarized, statistically analyzed using the arithmetic mean (the average), and presented in a matrix form for further quantitative analyses of the network relationships among the SCM established in each case project (see Table 3). This study examined all the stakeholders who participated in industrialized construction projects. All interviewees were well experienced in industrialized construction project collaboration and have relationships with the other stakeholders. A total of 28 professionals contributed in each case, including designers, contractors, precast concrete manufacturers, clients, and project managers (see Supplemental File 2). The length of each interview was approximately 30–50 min.

Table 3. Collaborative intensity matrix of stakeholders (arithmetic mean value of the input data)

Case A – Apt 16 building							
Participants	Client	Supervisor	Designer	Contractor	PC manufacturer	Specialty subcontractor	Supplier
Client	0	3.0	2.75	4.25	2.0	0	0
Supervisor	4	0	3.0	3.50	3.25	0	0
Designer	3.0	2.75	0	2.75	3.25	0	0
Contractor	3.75	3.0	3.0	0	3.50	3.5	1.75
PC manufacturer	3.0	2.5	2.25	2.5	0	0	0
Specialty subcontractor	0	0		3.0	0	0	1.5
Supplier	0	0		3.0	0	1.5	0
Case B – CMC special housing project							
Participants	Client	Supervisor	Designer	Contractor	PC manufacturer	Specialty subcontractor	Supplier
Client	0	3.75	0	4.25	0	0	0
Supervisor	4	0	4.5	3.75	0	0	0
Designer	0	0	0	4.5	4	0	0
Contractor	4.2	3.25	3.75	0	4.5	3.75	3.75
PC manufacturer	0	0	3.5	4.75	0	0	0
Specialty subcontractor	0	0	0	4	0	0	0
Supplier	0	0	0	4	0	0	0
Case C – Yi Hui Tang project							
Participants	Client	Supervisor	Designer	Contractor	PC manufacturer	Specialty subcontractor	Supplier
Client	0	3.75	3.75	4.25	3.5	0	0
Supervisor	5	0	1.5	3.75	0	0	0
Designer	4.25	0	0	3.75	3.75	1.5	0
Contractor	4.0	3.75	3.25	0	3.0	3.75	1.75
PC manufacturer	3.0	2.0	3.0	3.5	0	0	0
Specialty subcontractor	0	0	1.5	4.0	0	0	0
Supplier	0	0	0	2.0	0	0	0

End of Table 3

Case D – Dream-house project							
Participants	Client	Supervisor	Designer	Contractor	PC manufacturer	Specialty subcontractor	Supplier
Client	0	2.75	3.25	4.0	3.0	0	0
Supervisor	3.0	0	2.25	3.75	0	0	0
Designer	3.75	0	0	4.0	4.25	1.75	1.5
Contractor	4.0	3.75	3.75	0	4.0	3.25	1.75
PC manufacturer	3.5	2.5	3.75	3.75	0	0	0
Specialty subcontractor	0	0	1.75	3.5	0	0	1.5
Supplier	0	0	1.5	2.25	0	2.0	0

2.6. Evaluation of driving factors for SCM

The attributes that influence the SCM of industrialized construction were selected based on the relevant literature review (Ismail et al., 2012; Jiang et al., 2018; Li et al., 2018; Pan et al., 2007; Vibaek, 2014). Similarly to the categorization proposed by Costa et al. (2019) and Sparkling et al. (2017), the factors are organized into three categories: cultural, organizational, and industry-related, as shown in Table 4. It would be exciting and useful for practitioners to know the importance and the impact of each factor on the SCM and the interrelationships among them. The selected factors were further tested through semi-structured interviews with the ten industrialized construction experts (see Supplemental File 3). Then, the selected ten factors were evaluated by the 28 key actors (See Supplemental File 2) for their degree of importance based on the 5-point scale of measurement (See Supplemental File 5), and the analysis result of the mean value of the 28 actors is shown in Figure 3. The results revealed that design-construction efficiency, improving quality, and saving cost were the primary purposes of collaboration (see Figure 3).

Furthermore, 90% of respondents said that the DCE was one of the most important driving factors. This result revealed that DCE positively affected SCM; therefore, the result supported the hypothesis suggested in H2.

Table 4. Driving factors for SCM

Driving factors	Description	References
Cultural factors		
Enhance competitiveness	Unlike adversarial culture, which is based on a win-lose state of mind, promoting working together toward a joint objective	Bresnen and Marshall (2000), Tan et al. (2017)
Encourage innovation	Construction culture usually features conservatism and inflexibility, but there is a need for an innovative approach to teamwork solutions	Blayse and Manley (2004), Childerhouse et al. (2003), Sparkling et al. (2017)
Strength of alliance cooperation	Relationships focus on the long-term to improve cooperative relationships and profitability	Dubois and Gadde (2000), Ingirige and Sexton (2006), Ying et al. (2015)
Organizational factors		
Information and resource transfer	Information system and technological compatibility and effective organizational structures and culture	Quinn (1997), Sambasivan and Soon (2007), Stock and Lambert (2001)
Minimize cost	Parameters focusing on saving cost with overall efficiency beyond tendering fee, including collaborative ability, reputation, resources, competencies, and shared values	Eriksson (2008), Kadefors (2005), Sambasivan and Soon (2007)
Save time	Integration and system perspective for collaborative working tasks to save execution time	Briscoe et al. (2004), Fulford and Standing (2014), Harper et al. (2016)
Industry factors		
Expand market	Increasing opportunities for integration among the stakeholders and a wide range of construction services to ease the complexity and expand market	Dainty et al. (2001), Setiawan et al. (2015)
Design-construction efficiency	Optimizing the design and construction process in its use of material and components to provide maximum capacity at minimum cost	Adu and Opawole (2020), Indriani et al. (2020), Yap et al. (2020)
Technical barriers	Lack of technology and automation	Costa et al. (2019), Sooriyamudalige et al. (2020)
Quality improvement	The framework used to systematically improve standardized processes, structure to reduce variation and achieve predictable results	Ortega and Bisgaard (2000), Tam and Le (2007), Tchidi et al. (2012)

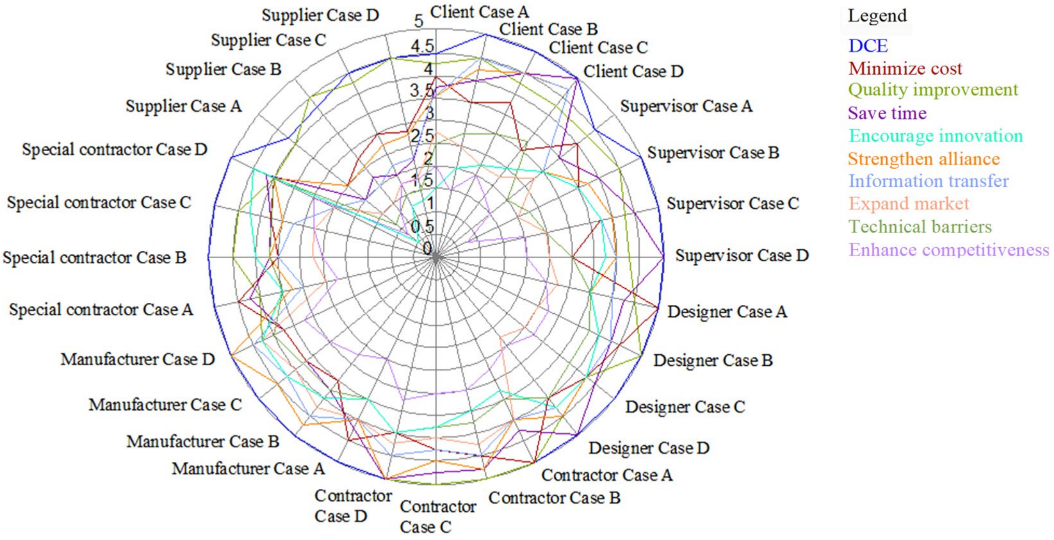


Figure 3. Importance level of driving factors for the SCM

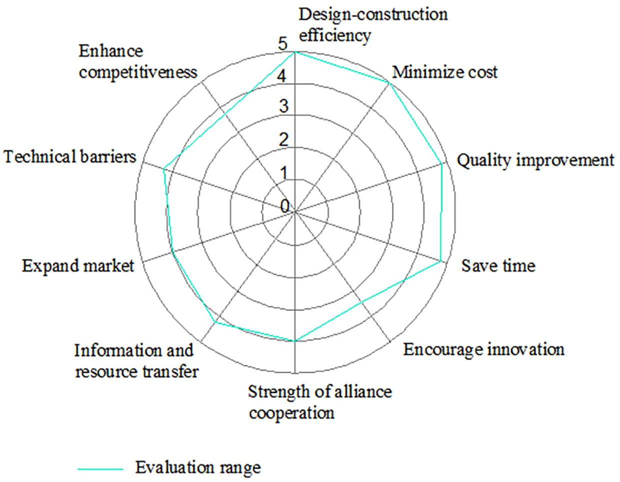


Figure 4. Importance level of driving factors for the SCM in each case project

Additionally, the stakeholders of the four project cases were also evaluated based on the importance level of the driving factors (see Figure 4). The result revealed that in each case, there are different levels of importance regarding the driving factors for the SCM. However, DCE has a higher value of importance in each case project.

3. Findings and discussions

3.1. Relationships between SCM and DCE

The DCE is intended to identify the degree of efficiency achieved by the SCM and its network relationships. It is evaluated based on the measurement factors such as integrated design, integrated construction, integrated management, and construction schedule. A five-point scale survey was undertaken with the selected 28 experts to quantify the degree of efficiency (see Supplemental File 6). The result in Figure 5 is the output of the degree of collaboration and interaction established in the network relationships among the SCM (see Figures 6–9). The results show that projects with strong SCM and network relationships have achieved better DCE (Nguyen et al., 2021; Xue et al., 2018b). In addition, projects having effectively established SCM saves time and cost by maximizing the product and delivery capacity of the actors involved (Xue et al., 2018a; Yu et al., 2019). For example, as shown in Figure 5, the strong SCM formed in case D contributes to better network relationships and improved performance of the DCE of the project. The degree of collaboration among the stakeholders increased in cases A, C, B, and D with an average collaboration tie strength of 2.98, 3.3, 3.95, and 4.18, respectively (see Figure 5). In addition, the analysis showed a direct relationship between the network relationship and each project's performance degree of DCE. Therefore, the result supported the hypothesis suggested in H1.

Similar to the previous studies, the results show that when there were strong SCM among the key stakeholders such as designers, contractors, manufacturers, specialized subcontractors, and clients, the higher the degree of integrated design, construction, management, and schedule of the project (Ismail et al., 2012; Jiang et al., 2018). This relationship was revealed in the project cases of B, C, and D (see Figures 5, 7, 8, and 9). As Vibaek (2014) discussed, the study also revealed that the strong SCM established among contractors, designers, precast concrete manufacturers, and specialized subcontractors helps to achieve a higher degree of efficiency in the construction schedule (Vibaek, 2014). This is shown in C and D project cases (see Figures 5, 8, and 9). Furthermore, in a situation where the interaction of suppliers and the specialized subcontractor was less, there was a reduction in the efficiency of integrated construction and integrated management (Nguyen et al., 2021). This was verified in the case of project A. In all project cases, the SCM analysis displayed that the contractor had a key central position and power to influence the improved performance of DCE positively.

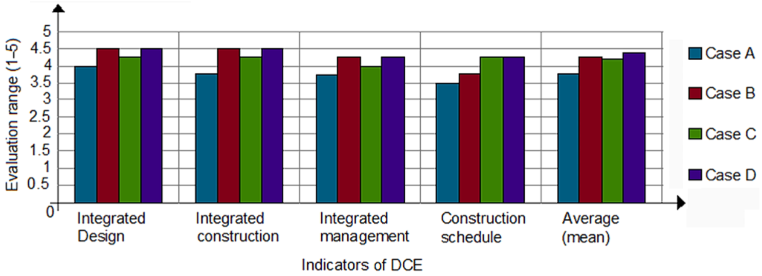
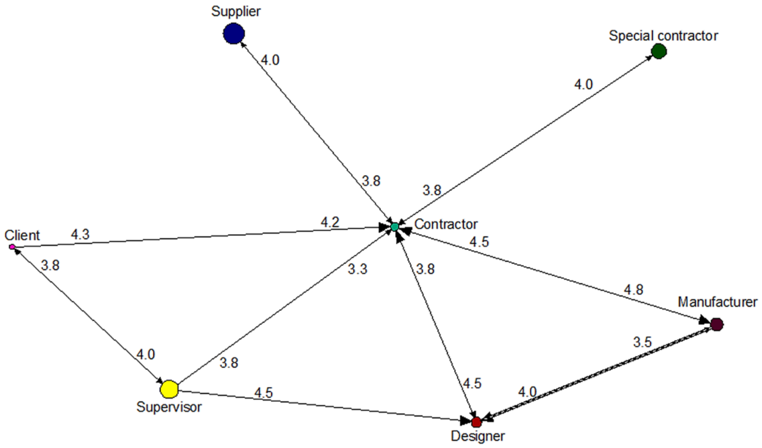


Figure 5. The degree of efficiency among the parts of DCE



Note: the numbers on the line show the influence of the node (the stakeholder or actor) near the number over the other end node (the other stakeholder or actor) linked by that line. In addition, two side arrow-headed lines indicate the influence of each node (stakeholders or actors) with each other linked by that line. Whereas, if the line is one side arrow-headed, it means that the node (the stakeholder or actor) at the initial point of the line influences the other node (other stakeholder or actor) located at the arrow-headed side of the line.

Figure 6. The SCM framework of case A

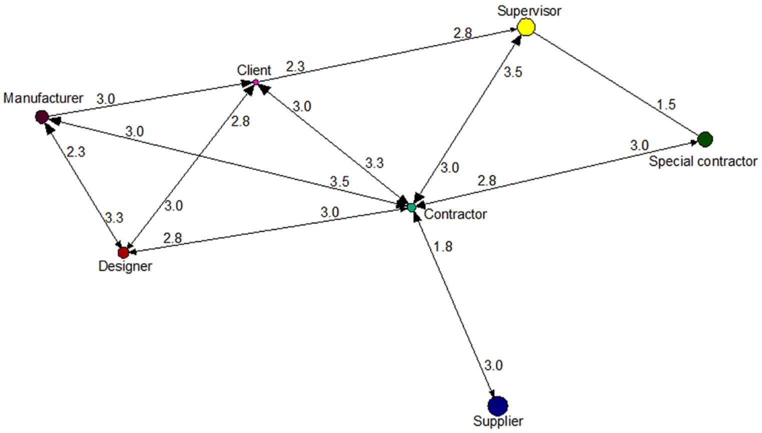


Figure 7. The SCM framework of case B

The primary goal of industrialized construction is to advance construction to achieve cost, time, and quality efficiency (Wu et al., 2021). As discussed briefly in Section 2.3, the application of the industrialized construction method in all project cases investigated in this study was to achieve a better DCE. This is expressed in terms of the projects' development intention, application of component-based design, use of prefabricated building components, and establishment of a different range of SCM. The collaborative intensity matrix of the SCM of each project (see Table 4) showed that the case projects have a diverse range of SCM intensity matrices which is also related to the project execution performance of the projects. For example, in the case of project case D, the project intended

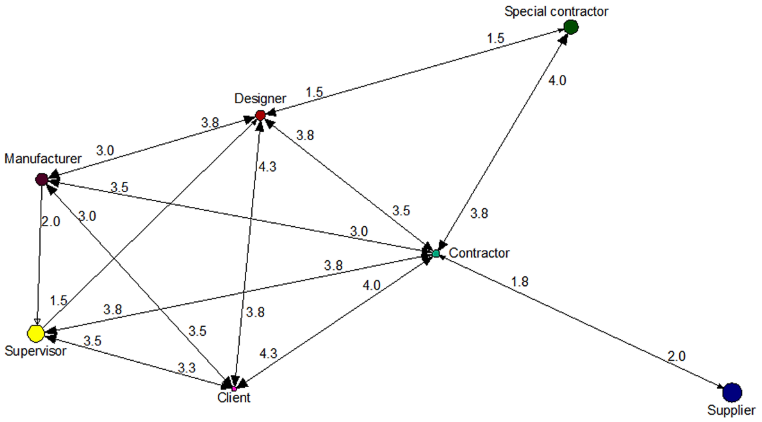


Figure 8. The SCM framework of case C

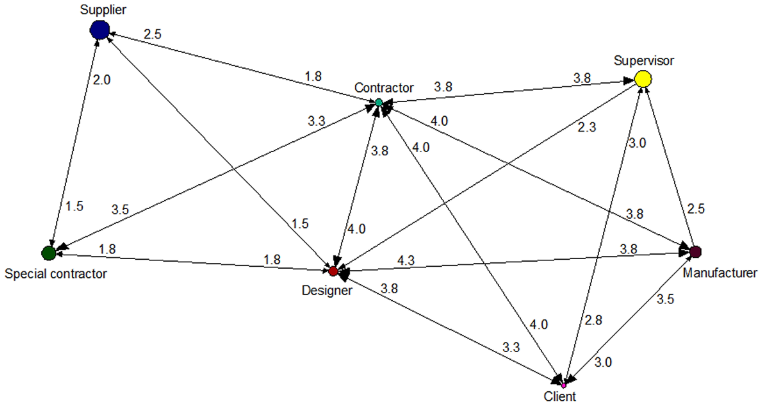


Figure 9. The SCM framework of case D

to complete the building within two weeks (see Table 1). As the bar of the execution plan was initially set high, the project team formed a very strong SCM (see Table 4 and Figure 9) from the early design stage and achieved a better DCE (see Figure 5). Therefore, the pursuit of better DCE performance improved the dynamic evolution of SCM. Therefore, DCE mapping supported H2.

3.2. Relationship between SCM and network relationships

A fundamental principle of SCM is to assist communication among professionals at various stages of the project life cycle to manage information and support the actors' roles (Xue et al., 2018b). Furthermore, SCM is promoted as an easing method, principally working with integrated project delivery, to offer opportunities for broader collaborations (Xue et al., 2018a). The network relationships and node attributes describe the position, strength, and function of SCM in industrialized construction projects. SNA delivers the graphical representation and numerical value of the network relationships and their key attributes, such as density, degree centrality, closeness centrality, and betweenness centrality (Xue et al., 2018a).

The network relationships' centralities value differs along with various contracting modes of the project cases (see Tables 6, 7, and 8). Generally, the variation of network relationships represented the different network structures of SCM established in the projects (see Figures 6–9). The SCM framework graphs were done based on UCINET 6, a software tool that helps to graphically analyze the social network relationships of actors within a given social entity (Haythornthwaite & Wellman, 1998). The graphical analysis contains the node position representing the actors connected by the lines representing the tie strength between the two actors. The tie strength is a critical concept in SNA that describes the intensity of a relationship (Haythornthwaite, 1996) when two actors exchange resources. The tie between actors can be measured and specified on the number of units in the graph line. It can be defined as either a weak or strong relationship depending on the SCM measuring values of frequency, familiarity, emotional intensity, and exchange of information (see Table 2 or 3) of that network relationships (Granovetter, 1973). The higher the value of the SCM attributes, the stronger the relationships will be. Although ties have often been referred to as weak or strong, the exact definition of what is weak or strong varies in particular contexts (Marsden & Campbell, 1984). The study results showed that the measuring factors of SCM and their level of strength among the actors define the overall graphical representation of the network relationships among the actors (see Figures 7–9).

The contractor has substantial value among other actors in terms of the measuring attributes of SCM (see Table 4). Furthermore, the strong value helped the contactor play a starring role due to its position (Chen et al., 2008) in communication and sharing resources among all other actors in the network relationships (see Figures 6–9). On the other hand, the supplier has a weak tie value regarding SCM measuring attributes (see Table 4). In fact, in the project cases of A, B, and C, it has no connection with other actors except the contractor. Therefore, the findings show that SCM positively affected network relationships. Thus, the findings supported the hypothesis suggested in H3.

3.3. Influence of network relationships on DCE

3.3.1. Density

When the density is higher, the network relationships and collaboration of the stakeholders will be stronger (Golob et al., 2013; Jalal & Koosha, 2015). The density of the projects investigated ranged from 1.1667 to 1.5774 (see Table 5), and their network centralization ranged from 47.39% to 68.54% (see Table 5). The density value shows a difference among the project cases in terms of the strength of the network relationships of the SCM. For example, project cases B and D had the strongest network of stakeholders' collaboration and had the highest density value (see Table 5). A stronger collaboration helps to improve the performance of the DCE of a project (Eriksson, 2010). In contrast, project case A had the weakest SCM and a comparatively low-density value.

3.3.2. Degree centrality

The total amount of direct links with the other nodes in a network graph measures the degree of centrality. It can be seen as a measurement of the communication activity of a stakeholder in a network relationship. One can also calculate network indegree and outdegree centralization. Indegree centrality is about an actor who receives many ties, which is characterized as prominent. The basic idea is that many actors seek to direct ties to them – and so this may be regarded as a measure of importance. While out-degree centrality is about an actor who can exchange with others, or disperse information quickly to many others. So, actors with high out-degree centrality are often characterized as influential.

Table 5. Social network structure metric

Metric	Case A	Case B	Case C	Case D
Density	1.1667	1.4940	1.3214	1.5774
Network centralization	47.40%	53.09%	49.27%	68.54%

The study result shows that (see Table 6), in each project, the contractors, designers, and clients had the relative higher centrality value and their importance within their network relationships and SCM. The importance is expressed through their control of the project process and its resources. While the degree centrality value of the supervisors, manufacturer, and specialty subcontractor is relatively low. Their relatively less value showed that their prominences and contributions as main actors to improve the performance of DCE become relatively low due to the increased collaboration caused by the high density of network relationships. In addition, the result (Table 6) shows that the contractor has the highest degree of centrality in all projects, which describes their importance in an industrialized housing project. The result also implies that the contractor is the most active contributor to the improvement of the SCM and the DCE because they have the most linkages to other actors in the network and can use their position to influence other actors to get more information.

3.3.3. Closeness centrality

The closeness centrality represents the degree to which an individual is near to all others in a network. It is the inverse of the sum of the shortest distances between each node and every other node in the network (Chapman & Corso, 2005; Golob et al., 2013). When an actor receives information close to many other actors, the value of the InCloseness centrality will be high. While an actor can quickly disperse information to many other actors, it will have a higher value of outCloseness centrality. The SNA result revealed that each stakeholder in their respective project cases has a more or less similar value of in and out closeness centrality (see Table 7). It also shows that each stakeholder had a similar inward and outward flow and exchange of information in each project case. It is related

Table 6. The degree of centrality of the network relationship of the case study projects

Participant stakeholders (actors)	Degree centrality							
	inDegree				outDegree			
	Case A	Case B	Case C	Case D	Case A	Case B	Case C	Case D
Client	57.843	55.882	57.143	28.772	57.843	50.980	38.095	28.070
Supervisor	35.294	35.294	32.143	24.561	34.314	35.294	29.762	42.982
Designer	51.961	63.725	38.095	41.228	51.961	59.804	42.857	29.825
Contractor	83.333	84.314	86.905	88.596	77.451	80.392	82.143	81.404
PC manufacturer	40.196	44.118	32.143	29.825	45.098	52.941	39.286	28.947
Specialty subcontractor	20.588	27.451	13.095	13.158	21.569	26.471	21.429	14.035
Supplier	6.863	18.627	8.333	13.158	7.843	23.529	14.286	14.035

Table 7. The centrality of the network relationship of the case study projects

Participant stakeholders (actors)	Closeness centrality							
	inCloseness				outCloseness			
	Case A	Case B	Case C	Case D	Case A	Case B	Case C	Case D
Client	75.000	75.00	75.000	60.000	75.000	75.00	66.667	60.000
Supervisor	66.667	66.667	66.667	60.000	66.667	66.667	60.000	66.667
Designer	100.000	100.00	66.667	66.667	85.714	85.714	66.667	60.000
Contractor	100.000	100.000	100.000	100.00	100.000	100.000	100.00	100.000
PC manufacturer	75.000	66.667	60.000	60.000	66.667	75.000	66.667	60.000
Specialty subcontractor	60.000	66.667	54.545	54.545	60.000	66.667	60.000	54.545
Supplier	54.545	66.667	54.545	54.545	54.545	66.667	54.545	54.545

to communication control regarding design specification, material purchase, and project management. In addition, some of the decreases in the closeness centrality of some stakeholders, like the PC manufacturers, happened across the project case. The decline is due to the increased distance between the stakeholder receiving and discharging information from other stakeholders in their network relationships. However, the contractor had the highest value of closeness centrality among all other stakeholders, representing its key star position in the network relationship in terms of receiving and discharging information among and to all other stakeholders. Although the contractors have the same closeness centrality value in all project cases, the contractors in project case A and case B had a significant role not only in constructing the building but also in the design, production, and supply of building components. Therefore, the closeness centrality value of PC manufacturers and specialty subcontractors in project cases A and B are relatively higher than that of the other two project cases.

3.3.4. Betweenness centrality

The betweenness centrality denotes the degree of control or brokering advantage a specific actor (node) can have over the communication flow (Abbasi et al., 2011). For all cases, the general contractors had the highest betweenness centrality value (see Table 8). The results showed that the contractors played an essential role being as a bridge in exchange for information and sharing of resources in the social network relationship as well as being the main actors of the on-site SCM of industrialized construction projects (see Figures 6–9) (Chen et al., 2008). However, compared to traditional construction, the role of the contractor in improving the performance of DCE on the onsite construction activity is less due to the introduction of shared and collaborative network relationships with the precast concrete manufacturers for the purchase and production of components (Lessing et al., 2015). In traditional construction, the contractor is the main decision-maker in the onsite construction process (Lee et al., 2014). Therefore, the contractor plays a significant role in keeping the network relationships of the project team to control the DCE of the construction. Whereas in industrialized construction, the decision on the onsite construction process involves all other stakeholders in the network relationships as the project is executed in collaboration with other stakeholders starting from the early design phase to the final construction stage of projects (Lessing, 2006).

Table 8. The betweenness centrality of the network relationship of the case study projects

Participant stakeholders (actors)	Betweenness centrality			
	Case A	Case B	Case C	Case D
Client	2.222	2.222	5.000	0.000
Supervisor	0.000	0.000	1.667	1.667
Designer	9.444	17.778	1.667	1.667
Contractor	47.222	25.556	65.000	80.000
PC manufacturer	1.111	1.111	0.000	0.000
Specialty subcontractor	0.000	0.000	0.000	0.000
Supplier	0.000	0.000	0.000	0.000

All the stakeholders in the network relationships of project D are more interconnected than the other three projects. This strong network relationship contributes to achieving a better DCE (see Figures 5 and 9). In the case of project A, the SCM framework analysis graph (see Figure 7) shows that two stakeholders, i.e., the supplier and the special contractor, had a direct connection to the contractor only. The contractor connects the rest of the stakeholders to these two stakeholders. This shows the less value of the density of network relationship and weak network centralization in project case A (see Table 5). The results in Table 5 and Figure 5 represent the corresponding direct relationships between the value of the density and network centralization of the projects and their corresponding level of the DCE. The increase in the density and network centralization of the projects increases the level of DCE. Therefore, a better collaborative network relationship among the stakeholders in industrialized construction helps improve the projects' overall DCE. This implied that the network relationships had a positive influence on improving the performance of DCE. Therefore, the study result supported the proposed H4.

Conclusions

The study explores the influence of network relationships among the SCM of industrialized construction projects and their effect on the performance of the DCE. Adopting the SNA method, quantitative and graphical analyses were done. The investigation of the impact of SCM on projects from a collaboration standpoint was done using rigorous network relationships with good empirical data that stemmed from four comparable industrialized housing projects. Based on the results of the study, the following conclusions are made.

SCM has a diverse impact on the role of the main actors. For the contractors, resource sharing and information flow from the component manufacturers and designers can solve the problem of node mismatches and reduce design alteration. In addition, in a situation where the interaction of suppliers and specialized subcontractors is less, there is a reduction in the efficiency of integrated construction and integrated management. Contractors and manufacturers have a vital role in controlling industrialized construction's integrated management and construction schedules. The designer and manufacturers influence the integrated design, while the contractor determines the integrated construction. Compared to the material supply mode of traditional construction, the precast concrete manufacturer has a crucial role in improving the efficiency of integrated industrialized construction. However, the contractors play a central role in better-transferring information and sharing resources that can improve the DCE.

Projects with strong SCM have better-integrated design teams of various professional experts, including component design, manufacturing, transport, and assembly experts. The design outcome of these experts improves the execution of the construction and project management process. It also saves time and cost by preventing significant design errors and wasting resources during construction. A good relationship among designers, contractors, manufacturers, and suppliers, can practice integrated construction and management. It also helps to complete the construction within the prescheduled time limit. Therefore, the study confirms the hypothesis proposed in H1 as SCM positively influences DCE. The study also showed that the most significant driving factor for the SCM is DCE. Projects with a great performance of DCE have a strong SCM among stakeholders for the effective integration of design and construction, which supports the hypothesis suggested in H2.

A deeper look into the network relationships shows that earlier project-stage relationships among stakeholders increase network relationships' efficiency by improving the project organization structure, resource sharing, and communication. In addition, projects with higher communication frequency increase the emotional intensity and familiarity among the project's main participants. It also increases closeness and information flow to strengthen network relationships. The result shows that SCM positively influences network relationships, confirming the proposed hypothesis in H3.

Projects with well-established network relationships save time and cost of the project by maximizing the product and delivery capacity. Additionally, the positions of precast concrete manufacturers, designers, and contractors in the network relationships significantly contribute to the higher performance level of DCE as they are core actors in most of the information flows. Furthermore, the network relationships' density, degree centrality, and closeness centrality determine the core, extent, and communication exchange. Therefore, the network relationships influence the DCE's performance, which confirms the hypothesis proposed in H4.

In conclusion, an important contribution of this study is that it not only validates the effects of SCM on the DCE of industrialized construction projects but also articulates the pathway through which such effects are made using empirical evidence and network relationships. In addition, it substantiates previous theoretical propositions of DCE on industrialized housing projects. The study is heuristic to scholars and practitioners interested in establishing effective SCM to improve the DCE of industrialized construction.

A limitation of this research is the small number of cases involved and studied in Ethiopia and China. The cases were limited because of a lack of availability and data access to industrialized construction. In addition, there are limited available experts in industrialized construction. To address the limitations of the low number of case studies and the possible bias of experts' response, a thorough investigation of empirical cases was conducted to collect the necessary data based on on-site visits, document reviews, repeated interviews, and survey questionnaires. Nevertheless, it is expected that the study shall contribute to the literature by establishing an evaluation method for the effect of network relationships among SCM for enhancing efficiency in industrialized construction projects. The method adopted and applied in the study can also be used in the broader global context. Therefore, this makes the study a common base for future research in DCE with more practical cases and multiple comparative studies. Further studies shall investigate the influence of network relationships on SCM behavior and the effect of the DCE on network relationships.

Author contributions

Yidnekachew Tesmamma Daget conceived the study and were responsible for the design and development of the data analysis. In addition, he was responsible for data collection and analysis. Hong Zhang and Yidnekachew Tesmamma Daget were responsible for data interpretation. Yidnekachew Tesmamma Daget wrote the first draft of the article.

Disclosure statement

There are no competing financial, professional, or personal interests from other parties.

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