Design Decisions and Interactions: A Sociotechnical Network Perspective

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Abstract: Effective interaction between project participants is essential in achieving a high-quality design. Through interaction, information is disseminated in project teams and the required knowledge becomes accessible during decision-making episodes. Consequently, effective interaction contributes to improved design outcomes and enhanced project efficiency leading to a higher chance of project success. Although interactions have been studied in the past, such studies predominantly focused on interaction patterns only, thus ignoring the decision-making context, participants' involvement, and the interdependencies between decisions. This paper makes a methodological contribution to the body of knowledge by proposing a sociotechnical framework. The framework enables the simultaneous investigation of decision interdependencies, the patterns of social interactions that address design knowledge requirements, and participants' involvement in and influence on making decisions. To demonstrate its efficacy, the framework was applied in a case study. The evidence suggests that design decisions with positive constructability outcomes could be achieved through an alignment between the information interdependencies of design decisions and the interaction patterns that underpin them. Involvement of participants with relevant knowledge and expertise and collaborative information exchanges between participants facilitated this alignment. The framework can be used in different project settings to analyze the theoretical mechanisms that characterize effective interaction in the context of design decision-making. **DOI: 10.1061/(ASCE)CO.1943-7862.0002136.**

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Introduction

An effective design process is crucial to achieving project success (Knotten et al. 2017). Proper design solutions enhance project efficiency by reducing the cost and time associated with redesign and construction rework (Pocock et al. 2006; Song et al. 2009; Li and Taylor 2014). Research evidence suggests that avoiding rework due to design errors can lead to cost savings of as much as 5% of the total project budget (Hwang et al. 2009). Similarly, considering the construction process during conceptual planning and design can help to avoid scheduling issues, delays, and disputes during the construction stage, leading to improved project performance (Arditi et al. 2002). The design stage also provides unique opportunities for enhancing workers' health and safety (Behm 2005; Lingard et al. 2014) and reducing construction waste (Baldwin et al. 2008). Consequently, an effective design process encompasses various project aspects and integrates diverse specialties into a holistic decision-making process.

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Integrated design demands that participants with different specialties work together to achieve common goals (Baiden et al. 2006). Collaboration and effective communication are necessary among design participants to make the right information accessible to the right participants at the right time, thereby improving the quality and accuracy of design decisions (Pektaş and Pultar 2006). Failures in delivering expected outputs in the early design stage are associated with poor communication, ineffective collaboration, not appreciating the complexity and interdisciplinary nature of the design process, and ill-informed decision-making (Austin et al. 2002).

Understanding interaction patterns and the way in which they underpin the design process can highlight opportunities for enhancing collaborative and effective interactions between design participants. This may be achieved by exploring the information requirements of design decision-making and encouraging interaction patterns which address these requirements more effectively. A network approach can facilitate this by providing valuable insights into the patterns of information dependencies and interactions in projects.

A network perspective has been applied widely in construction project management by viewing projects as network-based organizations (e.g., Chinowsky and Taylor 2012; Loosemore et al. 2020; Pryke 2012; Zheng et al. 2016) to understand their organizational behaviors and performance (Hansen et al. 2005). Network analysis has been particularly useful in understanding social patterns, interactions, and coordination between project participants (Brookes et al. 2006; Dogan et al. 2013; Kereri and Harper 2019), for example when participants develop design models using Building Information Modeling platforms (Zhang and Ashuri 2018). Network conceptualization has also been applied to study participants' interactions and negotiations during the design process (e.g., Chinowsky et al. 2008; Herrera et al. 2020; Lingard et al. 2014; Tryggestad et al. 2010). Critically, these applications have been exclusively cross-sectional and single-level, focusing on aggregated information exchanges over a project stage. Although providing insights about the interactions between design participants, this approach is limited in two aspects.

On the one hand, a cross-sectional or aggregated view of interactions within the design process ignores the dynamic nature of interactions, and the changes in interaction patterns at each decision point, as highlighted in previous research (e.g., Kereri and Harper 2019; Pirzadeh and Lingard 2017). On the other hand, merely focusing on participants' interactions (in a single level network) does not reveal explicitly the technical interdependencies between design decisions. However, these technical interdependencies are an important aspect of the design process because as design decisions build on each other, previous decisions influence subsequent decisions. To make appropriate decisions, design participants need to be aware of these interdependencies and the rationale for making earlier decisions. Hence, effective interaction between participants needs to enable the transmission of required information about previous decisions to participants involved in the subsequent related decisions. In other words, there needs to be an alignment between the decision interdependency patterns and the interaction patterns. Investigating the features of this alignment requires the simultaneous capture of both technical decision patterns and social interaction. However, the single-level network approach, predominantly used in previous research, does not capture both of these aspects of the design process.

To address this gap, a sociotechnical framework was developed by drawing on sociotechnical systems theory as well as network theory. The framework conceptualizes the design decision-making process as a multilevel network. It has a particular focus on the complexities of the design process, and addresses the way in which social interactions and technical interdependencies of design decisions are interrelated and evolve together. The framework was applied successfully in a comparative case study setting (using six cases selected from different industry sectors and procured using different approaches) to investigate features of effective communication in the context of design for construction safety (Pirzadeh et al. 2020). This paper presents the development of the framework and its detailed application in one case study.

The following sections review sociotechnical complexities of design decision-making. Based on this review, a theoretical multilevel framework is proposed to model and jointly investigate design decision-making and its underpinning interactions as a complex system. The framework emphasizes that design decisions and their underpinning interactions are highly interrelated; therefore, they are conceptualized as a sociotechnical system. Using a basic sociotechnical component of this system as the unit of analysis enables the investigation of the mutual interdependencies that exist between design decisions and their associated social interactions. Thus, it is possible to analyze the theoretical mechanisms (such as reciprocity, closure, and so forth) that characterize effective interaction addressing design information requirements. The efficacy of the framework was indicated using a case study.

Sociotechnical Interdependencies of Design Decision-Making in Construction Projects

Sociotechnical system theory recognizes the interdependence between the people and the technology in a work system (Klein 2014). Hence, by applying a sociotechnical system perspective in an organizational context, one can focus on structures of human (social) interactions, dependencies between technical elements, and the interdependencies between social and technical aspects (e.g., Davis et al. 2013). In construction, a sociotechnical system perspective has been applied, for example, to examine cooperative project delivery models (e.g., Tvedt 2019).

Construction design reflects the characteristics of a complex sociotechnical system. As Saurin and Gonzalez (2013) summarized, a complex sociotechnical system includes a large number of diverse elements, dynamic interdependencies between elements, unanticipated variability, self-organization to cope with the dynamic environment, and emergent properties which are beyond the characteristics of individual elements. Likewise, the design process involves a complex network of decisions (Rasmussen et al. 2019) made through ongoing interactions between design participants who reciprocate and build on each other's ideas while drawing on their distributed and mutually enclosed knowledge domains (Andersen 2016). Furthermore, the design process is dynamic. Throughout a project, there are ongoing and rapid changes to the design decisions which are not always anticipated or avoidable (Lin and Zhou 2020). The changes are made in response to the dynamic project environment and the availability of information, and to accommodate the requirements and constraints (e.g., time, cost, and available technology) imposed externally. Furthermore, participants' interactions vary throughout the design process as the knowledge requirements of decision-making change (Pirzadeh and Lingard 2017). The ultimate aim of this complex decision-making process is to achieve a high-quality design solution which best defines the features of the final product (i.e., building or facility), addresses different stakeholders' requirements, and guides the construction process (Gray and Hughes 2001); hence, the project outcomes, to a large extent, are shaped by (and emerge from) design decision-making. This section further reviews these characteristics.

Diversity of Design Decisions and Participants' Expertise

Design outcomes emerge from a network of interdependent technical decisions made through repeated interactions between multiple participants (Lingard et al. 2012; Nicolini et al. 2001). The interdependent nature of construction design was demonstrated by Austin et al. (2000), who identified about 800 tasks and 10,000 information dependencies in the design of a hospital project. Similarly, Austin et al. (2002) indicated 150 tasks and 1,500 information flows during the schematic design, and about 580 tasks and 4,600 information requirements in the detailed design process.

Modern design activity is increasingly multidisciplinary (Luck 2015), with each discipline constituting a community of knowing (Andersen 2016). Often, the knowledge required to make design decisions is held by multiple participants (Pektas et al. 2006). Design participants rely on each other's knowledge and decisions to fulfil the project's requirements (Dainty et al. 2006). In fact, design teams are referred to as "temporary, multidisciplinary and network-based organizations" (den Otter and Emmitt 2008).

Consequently, it is difficult and unrealistic to attribute design responsibilities to a single party (Lingard et al. 2011). This is evident in new forms of project coalitions in which design coordination role has moved away from a single designer (i.e., an independent consultant under the traditional procurement) to cluster leaders who coordinate groups of subcontractors and suppliers (Pryke and Smyth 2006). A reason for this change is the increased technical complexity of construction projects and the shifting of detailed design knowledge to lower levels of the supply chain (Pryke 2012).

Interactions and Knowledge Transactions during Design

Designing and engineering complex products, such as modern buildings and facilities, involves developing ideas and creative solutions to (often unanticipated) emergent challenges. Creativity involves knowledge creation. New knowledge is generated mainly by disseminating, transforming, and combining existing pieces of information through interaction between participants with varying areas of expertise (Kratzer et al. 2010; Reagans and Zuckerman 2001). Therefore, creativity is stimulated by coordinated interaction between project participants. Access to diverse types of knowledge (e.g., by engaging various specialists in the design process) can increase opportunities for sourcing and combining new elements of knowledge and information to develop nonroutine design solutions. This can be especially beneficial in situations in which decision-makers are dealing with unfamiliar design problems.

Design team interactions take various forms, e.g., formally exchanging emails and documents and attending formal face-to-face design team meetings, updating design models and sharing new information on Building Information Modeling platforms, or engaging in informal conversations while working on design tasks. Through these interactions, specialist knowledge embedded in project teams becomes useful knowledge for the development of creative design solutions (den Otter and Emmitt 2008). Furthermore, by integrating and organizing their distributed knowledge, project participants increasingly develop a common understanding of the design outcomes (Andersen 2016). Consequently, the process of social interaction (i.e., the transfer of information, opinion and ideas) between participants has been identified as a critical component of design activity (Austin et al. 2001; Herrera et al. 2020).

Interrelated Social and Technical Aspects of Design

There are ongoing and mutual influences between social and technical aspects of design decision-making. Fig. 1 indicates these reciprocal influences.

On the one hand, new design solutions emerge from social interactions, negotiations, and information exchanges between decision participants. Tryggestad et al. (2010) noted that construction design work is a reflexive and continuous process of (re)design activities. Design outcomes evolve through a flexible process of revisiting ambitions and engaging in trade-offs to find practicable solutions to emergent problems (Tryggestad et al. 2010). Thus, the decision network at the macrolevel evolves.

On the other hand, design participants engage in social interactions to discuss design decisions and exchange the knowledge and information needed for decision-making. Because of the different knowledge requirements of decisions, the interaction pattern at the microlevel repeatedly reconfigures during the design process (e.g., Pirzadeh and Lingard 2017). These reconfigurations enable participants to constantly align their knowledge compositions and information transactions with decision-making requirements.

Therefore, social aspect of design decision-making and the technical aspect are interrelated. A systems perspective was used in this paper to capture these interdependencies. Project participants and design decisions are the elements of this conceptualized system. To enable effective decision-making, the structure of interaction networks needs to (1) provide access to suitable sources of knowledge through involvement of participants with relevant expertise; and (2) facilitate the combination of knowledge elements through participants' information exchanges and negotiations from which the decision outcomes emerge. At the same time, these knowledge transactions need to suit the knowledge requirements of design decisions. Thus, the effectiveness of the design system depends on the interplay (and joint optimization) of the network of interactions between participants and the knowledge requirements of interrelated technical decisions.

From this perspective, design effectiveness can be conceptualized as an emergent property of the whole system reflecting the system's ability to produce desired design outcomes while coping with the constraints imposed by the project environment (such as cost, time, site restrictions and available technology and material). Therefore, by jointly studying design decisions and social interactions and by analyzing the ways in which they are aligned during the design process, it is possible to associate these sociotechnical interdependencies with design effectiveness.

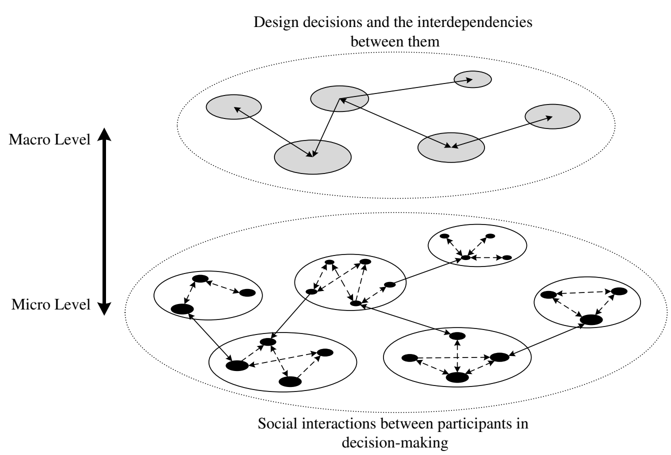


Fig. 1. Design sociotechnical system representing the interdependent social and technical aspects of design decision-making. (Reprinted from Pirzadeh 2018.)

Sociotechnical Framework Representing Design Decision-Making as Multilevel Network

Based on the discussion in the previous section, a new theoretical framework was developed and used to model interdependencies between technical decisions and social interactions during design processes and to investigate their influence on design outcomes. The framework is based on the perspective that

1. social and technical aspects of design decision-making are highly interdependent; therefore, they should be viewed as an integrated sociotechnical system; and
2. design effectiveness is an emergent outcome arising from influences and interactions between social and technical elements and is observed at the system level.

The framework [Fig. 2(b)] captures the complete set of relationships between social and technical system elements. In doing so, it adopts a multilevel network view [Fig. 2(a)] to model the system. The sociotechnical system consists of (Pirzadeh 2018)

- technical decisions and their interdependencies (at the macrolevel);
- participants (i.e., actors in network terminology) and the social ties between them (at the microlevel); and
- the links between social and technical components (at the mesolevel).

Presence of a social tie between two actors indicates interaction and information exchange between them. The direction of the tie shows the direction of information flow. Technical ties signify the

J. Constr. Eng. Manage., 2021, 147(10): 04021110

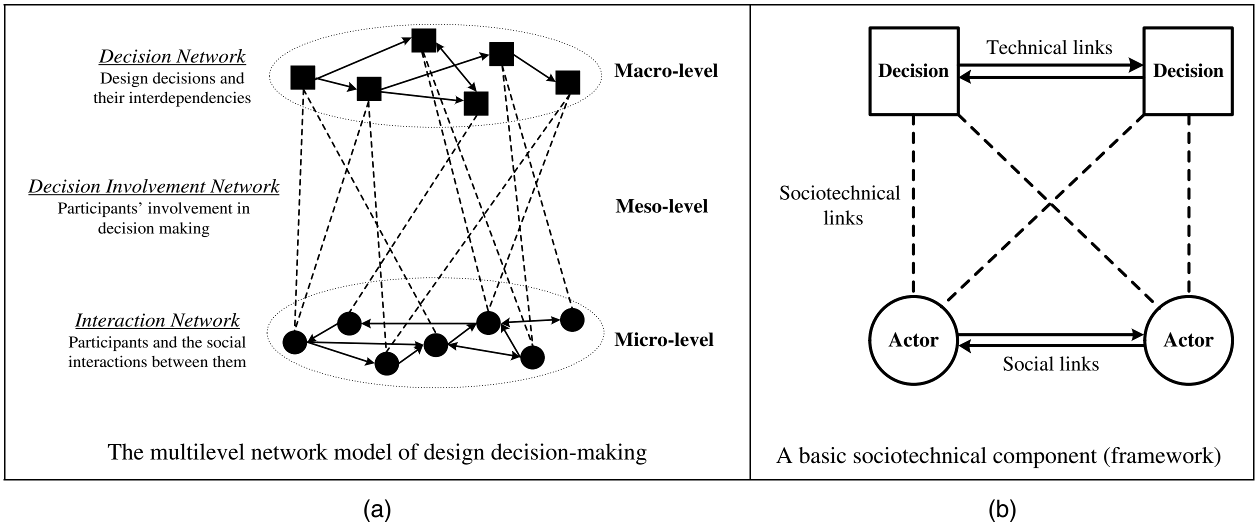


Fig. 2. Sociotechnical framework representing design decision-making as a multilevel network.

logical and information dependencies between decisions as they build upon each other in an iterative creative process. An actor's influence on shaping a decision outcome is defined as a sociotechnical tie between the actor and a technical decision. This is captured by mapping actors' participation in decision-making scenarios and measuring their power relative to other decision participants. Using these specifications, the most basic sociotechnical network component consists of two actors and two decisions. This component is indicated in Fig. 2(b).

This framework can be used to conceptualize the interdependency patterns between design decisions and participants as network configurations (Fig. 3). These network configurations signify particular social processes. Assessing the prevalence of these interdependencies during the design process can reveal the dominant social processes that influence design decision-making. For example, it is possible to assess the implications of participants' reliance on reciprocal communication and closure, and compare these with situations in which knowledge brokering is the dominant social process during design decision-making. The dominance of each social process has implications for the way in which technical information and knowledge is made accessible in a design situation. This, in turn, can impact design outcomes.

The multilevel network approach provides more precision by simultaneously analyzing both the within-level and between-level relationships in complex systems in which interdependencies exist between the macro- and microlevels. In such systems, analyzing within-level relationships separately would lead to losing insight about features of the bigger picture, i.e., the whole system and its characteristics. (Moliterno and Mahony 2011; Snijders 2016; Wang et al. 2013). In the next section, the theoretical framework is applied in a case study.

Methodology

The multilevel framework was applied in a multiple case study analysis. The case studies focused on the design and construction of specific building elements. For each case, a convergent mixed method design (Creswell 2015) was employed by collecting qualitative and quantitative data and merging the results of their analysis. Only one of the case studies is presented in this paper, because the aim of the paper was to introduce the multilevel framework and indicate its application. The case involved the design and construction of a façade structure for a 42-story high-rise building.

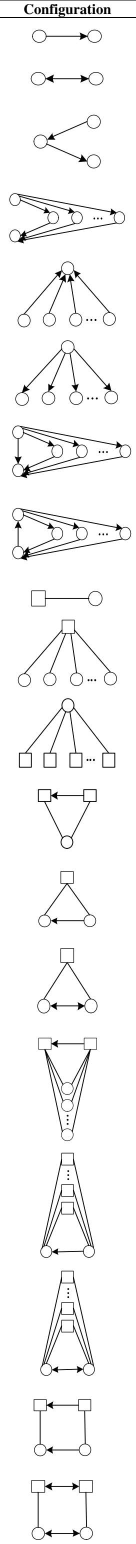
For the case study reported in this paper, initially six in-depth interviews were conducted. Interviewees were key project participants: the project manager, design manager, construction manager, architect, design engineer, and services engineer. Participants were asked to describe the project and their roles in it. They also were asked to identify key decisions in which they were involved during the design and construction of the façade, the circumstances within which each decision was made, and the outcomes of the decision.

The interview data were analyzed to identify the context and nature of key design decisions and to reveal the rationale and interdependencies between decisions. A narrative was developed describing the key decision-making episodes and the outcomes. A decision was identified as the point at which a technical choice was made between two or more possible options. In addition, a network diagram was developed showing the interdependencies between the decisions (Fig. 4). The nodes in this network were the discrete design decisions. A link between two decisions was established if there was a logical and/or information dependency between the decisions. For example, the material and length of vertical structural elements was specified based on the façade frame layout and the construction method while accounting for the transport and constructability (mainly lifting and access) requirements. Therefore, these decisions were linked in the network. The interview data were triangulated by comparing different interviewees' statements. The statements were verified further when inconsistencies were found. This approach helped to reduce the impact of self-reporting bias, and to avoid overreliance on one interviewee (Yin 2009).

To explore participants' interactions and involvement in decision-making, social network data were collected. Using name generators, the interviewees were asked to identify participants with whom they interacted for each key decision; thus, participants in each decision were identified. The following inclusion criteria suggested by Pryke (2005) were used: (1) the participant's organization was a member of the project coalition and actively was involved in making project decisions, and (2) the frequency or importance of interaction between the participant and at least one other design participant was perceived to be significant.

The participants then were asked to rate the frequency and importance of their interactions with each of the other participants at

Parameter	Configuration	Interpretation in this study
Arc		Refers to the baseline tendency for formation of social interaction ties (density)
Reciprocity		Mutual interaction between participants, tendency for reciprocated (two-way) interaction between the actors
Simple connectivity		Refers to the extent to which social actors who send out information also receive information.
Multiple connectivity		Indicates the extent to which actors interact indirectly through others, forming multiple short paths between actors.
Popularity spread		Indicates the presence of actors who are highly central in receiving information from others (reflects the extent of in-degree centralization in the network).
Activity spread		Indicates the presence of actors who are highly active in sending information to others (reflects the extent of out-degree centralization).
Triangulation (Transitive closure)		Indicates the tendency for social closure in network; that is, interaction tends to happen in multiple clusters of triangles; thus, the interaction distance in the network would be short.
Cyclic closure		Reflects the tendency for social interaction to occur in non-hierarchical cycles.
Cross-level edge (tie)		Indicates the baseline tendency for actors' involvement in decision-making.
Cross-level connectivity spread (decision popularity)		Indicates the presence of central decisions in which a high number of actors are involved.
Cross-level connectivity spread (actor popularity)		Indicates the presence of influential actors in network who are involved in several decisions.
Affiliation-based (cross-level) closure arc (dependence)		Indicates actors' tendency to be involved in interdependent decisions; that is, tendency for dependent decisions to involve the same actor.
Affiliation-based (cross-level) closure arc (interaction)		Reflects the tendency for decision-involvement and social interaction to create closure; that is, tendency for actors involved in the same decision to interact with each other.
Affiliation-based (cross-level) closure reciprocity		Indicates the tendency of actors making the same decision to engage in two-way interaction.
Alternative affiliation-based closure arc (decision dependence)		Indicates the extent to which dependent decisions involve a number of the same actors who are involved in both decisions.
Alternative affiliation-based closure arc (actor interaction)		Reflects the extent to which actors who are both involved in a number of the same decisions tend to interact directly.
Alternative affiliation-based closure reciprocity		Indicates the tendency for actors who are both involved in a number of the same decisions to engage in two-way interaction.
Cross-level alignment entrainment		Indicates a tendency for actors who are involved in different (but dependent) decisions to interact; that is, the extent of alignment between decision dependencies and interactions.
Cross-level alignment reciprocity		Indicates the tendency for actors who are involved in different, but mutually interdependent, decisions to engage in two-way interaction.



Note: Squares indicate decisions and circles indicate participants (actors)

Fig. 3. Exponential random graph parameters used in this study and their interpretation. (Adapted from Wang et al. 2013, 2014; Pirzadeh 2018.)

each decision point. The participants were advised to consider all types of formal and informal communication. For each decision in which they were involved, they were asked to identify other participants with whom they interacted and indicate the frequency of their interactions using a 5-point Likert response format ranging from 1 (occasionally) to 5 (daily). For each interaction instance, they also were asked to explain the importance of the exchanged information. The importance then was rated on a 5-point scale. Scores 1 and 2 indicated that the information was either not important or had little impact on decision-making. Scores 3–5 respectively indicated that the information was somehow important, needed, or highly important to decision-making. Furthermore, for each decision, participants were asked to nominate those whom they considered to be the most influential participants and rate them (on a 5-point scale) from greatest influence to least influence on decision-making. A participant's decision-making power was then calculated at each decision point by adding the rates received and averaging the result to a range from 0 to 5.

Social network analysis was used to map interaction patterns between participants. Using the framework in Fig. 2, the decision network and interaction network were combined to develop a multilevel network. The macrolevel network consisted of the design decisions and the interdependencies between them (Fig. 4), reflecting the technical interdependencies of design process. The microlevel network represented the social interactions that took place between the participants during the design process. The mesolevel network indicated the involvement of participants in decisions based on their decision-making power. That is, a tie between a participant and a decision was established if the participant's decision-making power was greater than zero, indicating that the participant was involved in, and had an influence on, making the design decision. Consequently, the multilevel network reflected the sociotechnical complexities of design process by comprising two types of nodes (design decisions and design participants) and three types of relationships between them (technical interdependencies between decisions, social interactions between participants, and participants influence on decisions). With this multilevel network conceptualization, the next step was to conduct an in-depth analysis of the interdependency patterns which characterized the network. To achieve this, exponential random graph models (ERGMs) were used.

ERGMs are a type of statistical models which can be used for examining multilevel and multitheoretical hypotheses about network formation (Robins et al. 2007). They can provide insights into the underlying social processes that develop and maintain network-based social systems (Robins and Lusher 2013b). Using ERGMs, a set of basic local tie-based structures (referred to as configurations) are selected. These configurations represent social processes which may shape global network patterns (Lusher et al. 2013). Thus, by identifying these local configurations in an observed network pattern and assessing their prevalence, it is possible to test hypotheses about the network formation. To do this, the observed network is compared with networks of a similar size which are generated by statistical simulation. A low probability of observing the same network pattern by chance provides confidence in the presence of the hypothesized social processes in the network under study (Scott 2012). The basic configurations and the social processes they reflect in the context of this study are indicated in Fig. 3. During the analysis, the interaction data were dichotomized. MPNet software version 1.04 (Wang et al. 2014) was used to specify and analyze the multilevel ERGMs.

Results

Case Context

The case focused on the design and construction of a high-rise façade structure for a 42-story residential building. A design and

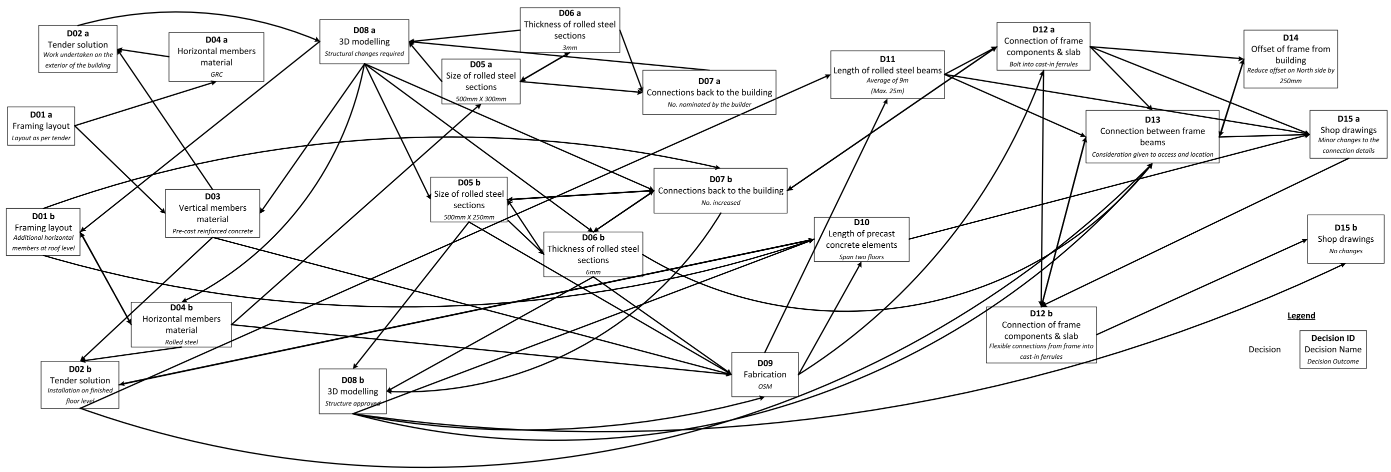


Fig. 4. Decision network for the design of high-rise façade system. (Reprinted from Pirzadeh 2018.)

construct (D&C) procurement approach was used. The client engaged an architect and a structural engineer to develop a preliminary design. The façade structure was self-supporting and had a number of nonroutine features which required special consideration. These features included a unique architectural design, use of a construction material not previously used for a high-rise façade [i.e., glass-reinforced concrete (GRC)], strong wind in the area, and very limited space in an inner-city site. These features restricted the options available for structural details (e.g., required special structural connection details) and for construction methodology, and created several health and safety challenges. Consequently, in this case study, constructability and health and safety were key indicators of design effectiveness.

After involvement in the project, the constructor raised issues about the structural design, the construction methodology, and workers' health and safety. Subsequently, a number of design aspects were revised. For example, the constructor nominated rolled steel, folded into a rectangular shape, as a substitute for GRC. The constructor also proposed to manufacture the frame members off-site. These decisions led to modifications in the dimensions and arrangements of façade elements, as well as in the design of element connections and intersections. The design modifications facilitated a revised sequence of work which enabled floor-by-floor installation of the façade elements as the building was vertically constructed. This method improved the installation speed and eliminated the need for installers to work on the outside of the building at a height of 130 m.

Fig. 4 indicates the design decision network. Each decision is shown by a rectangle. Letters (a, b, or c) after the decision IDs denote revisions to the same decision. Each rectangle also includes the decision name and the decision outcome (selected option) under the decision number. Links between decisions indicate logical and/or information dependencies.

Overall, the design revisions were perceived to improve the construction process and addressed the client's requirements and the architect's intent. This was evident from the design manager's comment that

> Architecturally and aesthetically the [façade] element was going to look exactly the same as what it was under the previous design, it was just a better fabrication, installation, construction process and enabled us to tick those boxes, and budgetwise it was good as well.

Exploring participants' involvement in decision-making

The mesolevel relationships were mapped using the bipartite graph in Fig. 5, in which the circles represent the project participants and the squares indicate decisions. The decision IDs provided in this figure are consistent with the IDs specified in Fig. 4. A link between a participant and a decision in Fig. 5 indicates that the participant had power to influence the decision outcome (as perceived by other participants).

On average, making each decision involved nearly five participants. Revising the framing layout (Decision 1b) and revising the size of rolled steel sections (Decision 5b) involved the highest number of participants, eight and seven participants, respectively. In addition, Decisions 5a, 6b, 7b, 8b, and 12b each involved six participants. These decisions included revisions to façade framing layout, the size and thickness of steel members, the type and number of connections, and the three-dimensional (3D) structural model. These decisions enabled revising the construction methodology, which improved constructability and work health and safety (WHS) outcomes.

On average, each participant was involved in nine decisions. The most influential participants were the project manager, design manager, and construction manager—each was involved in 23 decisions. The client was involved directly in the concept design decisions; however, during the detailed design, the architect and the design engineer represented the client. The architect was influential in 16 decisions, and the design engineer influenced 10 design decisions. The steel subcontractor and steel supplier were involved in specifying details of the steel elements, their connections, and the façade layout.

Analyzing Patterns of Interdependence within Multilevel Network

Applying the framework introduced in Fig. 2, a multilevel network was developed. To analyze the formation of the multilevel network, ERGMs were used. Two models were fitted to the data. The first model included all the interactions between participants, and the second model included only important information exchanges, i.e., the second model comprised only interaction ties with an importance value greater than 2, indicating that the information was important and needed for decision-making.

In both models, goodness-of-fit t-ratios had absolute values less than 0.1 for fitted effects and less than 1 for unfitted effects.

J. Constr. Eng. Manage., 2021, 147(10): 04021110

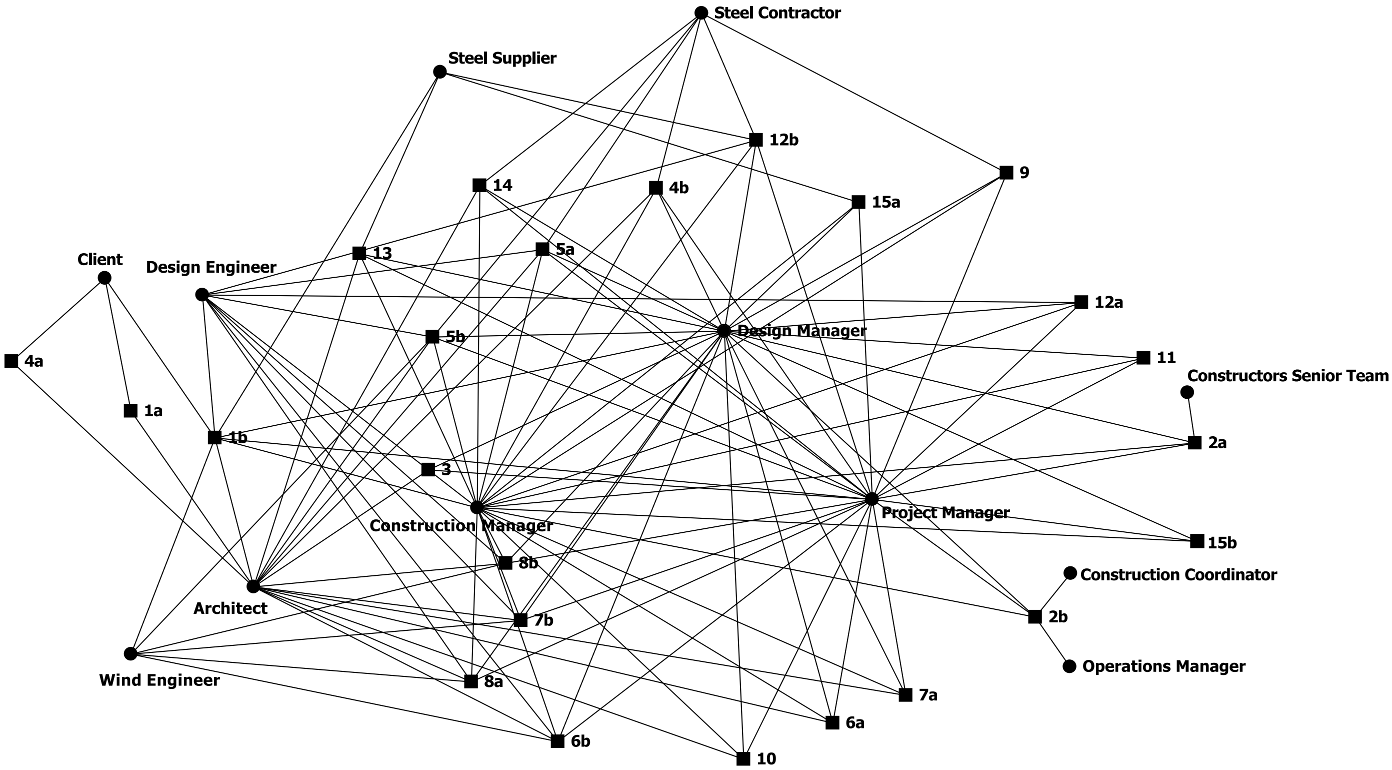


Fig. 5. Participants' involvement in decision-making. (Reprinted from Pirzadeh 2018.)

Table 1. Parameter estimates for ERGMs

Effect	Model 1	Model 2
Interaction-level effects		
Arc	9.5934 (10.894)	−3.703 (2.626)
Reciprocity	**6.0287** (2.084)[a]	**4.8638** (1.904)[a]
Two-path	0.2535 (0.251)	0.2177 (0.154)
Popularity spread	−0.2796 (2.177)	−1.4175 (1.048)
Activity spread	−11.1644 (5.953)	−2.1914 (1.14)
Transitive closure	1.8393 (1.012)	**2.2193** (0.76)[a]
Cyclic closure	−0.2729 (0.881)	−0.7311 (0.417)
Multiple connectivity	0.3115 (0.412)	0.2506 (0.207)
Cross-level effects		
Cross-level edge	0.585 (4.771)	1.4392 (4.534)
Cross-level three-star connectivity (decision popularity)	−0.0749 (0.075)	−0.0903 (0.073)
Cross-level three-star connectivity (actor popularity)	0.0042 (0.003)	0.005 (0.003)
Cross-level connectivity spread (decision popularity)	−3.6476 (2.719)	−2.7501 (2.572)
Cross-level connectivity spread (actor popularity)	0.8008 (1.135)	−0.3454 (0.94)
Affiliation-based closure arc (dependence)	**0.8378** (0.216)[a]	**0.7372** (0.223)[a]
Alternative affiliation-based closure arc (decision dependence)	0.2675 (1.153)	0.669 (1.172)
Affiliation-based closure arc (interaction)	0.4976 (0.424)	0.4598 (0.423)
Affiliation-based closure reciprocity	0.0199 (0.709)	0.0467 (0.671)
Alternative affiliation-based closure arc (actor interaction)	1.929 (1.071)	1.6003 (1.026)
Alternative affiliation-based closure reciprocity	−2.5776 (1.892)	−2.5238 (1.944)
Cross-level alignment entrainment	**−0.0493** (0.018)[a]	**−0.0459** (0.019)[a]
Cross-level alignment reciprocity	0.1323 (0.068)	**0.1655** (0.078)[a]

Source: Reprinted from Pirzadeh (2018).

Note: Standard errors provided in parentheses. Bold figures indicate significant effects for which the parameter estimate exceeds twice the standard error (in absolute value).

[a]Significant estimate.

These values are well below suggested thresholds (Borgatti et al. 2013; Robins and Lusher 2013a), and indicated that both models were capable of reproducing the properties of the observed network. Parameter estimates for the models and their corresponding standard error are presented in Table 1. Significant parameter estimates indicate that the social process represented by that configuration was likely to be present in the case study project network.

The positive and significant reciprocity estimate indicates that design decision-making was predominantly underpinned by two-way information exchanges between participants. The reciprocity effect was significant in both models. The interaction data indicated that the majority of the two-way interaction happened between design manager, construction manager, and project manager.

Engagement in frequent reciprocal information exchanges enabled these senior participants to coordinate the structure design, construction process, and project plan. An example was revising the frame layout, during which the project manager, design manager, and construction manager interacted frequently with each other. This design revision was needed to improve the lateral stability of the façade (structural design) while considering the lifting process of frame elements and workers' safe access to install additional frame members (construction process). These, in turn, required the consideration of connection locations (structural design) as well as coordinating the offsite manufacture of additional structural elements and considering their safe transportation and installation (project plan) when deciding the length of manufactured structural elements (structural design).

The positive and significant transitive closure estimate in Model 2 can be interpreted as the effect of a "path shortening process" (Robins et al. 2009) encouraging the formation of clusters of triangles in the network. In other words, the important interactions tended to happen directly in local groups of participants. Because Model 2 included only the important interactions, the significant closure effect can be evidence that the important information exchanges were shaped by collaboration in local groups (Robins et al. 2012). Moreover, the transitive (rather than cyclic) nature of closure suggests that the information exchange tended to happen in a hierarchical arrangement in local groups of design team members. Examples include the interactions underpinning the design of horizontal and vertical frame members and their connections. When making these decisions, the project manager, design manager, and construction manager interacted directly and formed a triangle of strong ties at the core of the interaction networks. Each of these three senior managers also engaged in local interactions within their disciplines (e.g., design manager with design engineer and wind engineer) or with external subcontractors (e.g., construction manager and project manager interacting with steel supplier and steel subcontractor). These interactions formed triangular structures on the peripheries of the frequent interactions among the three senior disciplinary managers. Through clusters of these local (disciplinary) interactions, specialized knowledge and expertise were integrated within each discipline and subsequently were applied in the decision-making process, mainly through the interactions between the discipline managers.

The positive and significant estimate for affiliation-based closure in cross-level effects indicated that participants were likely to be involved directly in and to influence interdependent decisions. Furthermore, the negative and significant estimate for cross-level alignment entrainment reflects a low tendency for participants involved in different, but interdependent, decisions to exchange information directly. When interpreted together, these results suggest that the interdependent decisions were more likely to be made through direct involvement of common participants. In other words, the associated information was more likely to be transferred between dependent decisions through direct involvement of individuals rather than only through interaction between them. Consequently, for decisions that technically depended on each other, the individuals were the primary means of transferring the relevant knowledge among the decisions. For example, the design manager, construction manager, project manager, and architect who influenced the specification of framing layout also were influential during the specification of the construction material for the horizontal structural members, the number of connections between the façade frame and the building, and the length of precast concrete members. All these decisions required information from the framing layout. The same participants also were influential in revising the construction methodology to safely install the frame members floor-by-floor.

Another example was the steel supplier's influence on the design of connections between the frame and floor slabs. The steel supplier suggested using a cast-in sleeve-type connection which made the installation process quicker and eliminated the need for welding and drilling at height. This decision affected the design of connections between frame beams, during which the steel supplier also was influential, and suggested using OrbiPlate connectors (Reid, Victoria, Australia) to provide more flexibility during installation.

Discussion

Involving Internal and External Sources of Knowledge and Expertise in Decision-Making

The combined investigation of the decision circumstances, outcomes, and the interaction patterns revealed a number of features. Construction methodology was considered as part of the design decision-making from the tender stage. The constructor raised concerns about the structural stability, constructability, and safety aspects of the preliminary design when preparing their tender response. They made some internal financial allowance for further revision of the proposed design. Furthermore, as both the interviews and the network patterns indicated, the involvement of senior participants with extensive construction experience in the design revision process was beneficial to improving constructability and health and safety performance of the design. As the design manager explained

> So [we] tendered it and priced it as per the architectural drawing, but we made internal allowances for further design development, you know, engineering input, and the like. Once we were formally awarded the project ... we had a bit of a design review with some of our senior guys and the project team, and we had a fundamental position that we didn't believe that that design was going to be the right approach for us to build the job and so the decision that we were coming from was how do we best design this element to fit into our construction requirements.

The multilevel network pattern revealed both the use of internal knowledge and resources within the design team and the inclusion of external specialist expertise when required. On one hand, the prevalence of direct and two-way communication ties (evidenced by the significant closure and reciprocity effects) led to a highly connected interaction network. This reflected a fast and efficient flow of information among participants from the constructor's organization and the architect and engineering consultants. Frequent and reciprocal interactions also were observed between the project manager, design manager, and construction manager. These enabled them to coordinate the decision-making, whereas their high influence and involvement in most of the design decisions enabled them to govern the design process.

On the other hand, involvement of suppliers and specialist subcontractors helped to incorporate innovative solutions where and when required. For example, revisions to the connection details suggested by the steel subcontractor improved the stability of the structure as well as constructability, and reduced installation time.

Suppliers and subcontractors also brought knowledge about construction and fabrication processes to the design decision-making process and identified practical issues. For example, referring to the steel supplier who prepared the shop drawings, the architect commented

> So they make sure that everything is drawn, like just minor connection details and all of that. . . . I actually find that it's the important part of all this to making sure that it works thoroughly, because they have the construction knowledge and the manufacturing process, they know all of that thing. Whereas we, on the other hand, we know the aesthetics, we know what we need to achieve, but we're not necessarily the expert in manufacturing and fabrication.

Collaboration between participants was identified as an important factor in achieving a high-quality design that incorporated different parties' interests and was constructible. In particular, the collaboration of the constructor's team with the client and the architect was highlighted. As the construction manager explained

> When we tendered [for the project], we put a PC [prime cost] sum on it and we qualified ourselves out of the whole thing working. So, we were in a box seat really with the client and with the architect to say, you know, we'll do our best to make your impossible spider web work, but you've got to work with us.

Reciprocity and Closure

The collaborative nature of design and the underlying interactions was evidenced further by the multilevel network analysis. The positive and significant reciprocity effect highlights the prevalence of two-way information exchanges between participants. Furthermore, the positive and significant transitive closure effect reflects the collaborative interaction pattern in which participants tended to cooperate and exchange information in local teamlike configurations. Reciprocity and network closure have been regarded in previous studies as indicators of trust in teams (e.g., Terhorst et al. 2018; Lusher et al. 2014). Moreover, network closure has been interpreted as a sign of collaborative behavior leading to enhanced cooperation (Lubell et al. 2011). Through social closure, the disciplinary knowledge and information could be integrated within local (disciplinary) teams and were further disseminated across disciplines through interactions between discipline managers who acted as bridges facilitating interdisciplinary interactions and as gate keepers controlling the disciplinary interactions.

Throughout the design process, the prevalence of closure and reciprocity effects led to the development of a cohesive interaction network pattern favorable for enhanced information mobility and improved performance (Obstfeld 2005). This, in turn, enhanced shared understanding and collective problem-solving (Schilling and Phelps 2007) with involvement of expertise from multiple disciplines. Furthermore, the hierarchical nature of interaction, evidenced by the prevalence of the transitive closure effect, reflected the discipline managers' governance on the overall interaction ensuring the exchange of relevant information and avoiding information overflow.

Participants' Involvement to Transfer Knowledge Directly among Interdependent Decisions

The significant and positive affiliation-based closure effect highlights participants' ability to directly influence the decision outcomes when their skills were relevant. The prevalence of this effect in the network creates a match between decision dependencies and participants' expertise and facilitates a direct and efficient transfer of knowledge between technically dependent decisions.

Design problem-solving normally requires the transfer of tacit knowledge between multiple project participants, and across disciplinary boundaries (Dossick and Neff 2011). However, it is hard to articulate tacit knowledge and transfer it to others, because it is embedded mainly in individuals' experiences and held in their minds (Nonaka and Takeuchi 1995).

Directly involving relevant participants in making dependent decisions enables the mobility of knowledge sources between the decisions and can enhance the transmission of tacit knowledge; that is, the how and the why, in addition to the what (Pirzadeh et al. 2020). For example, in this case study, the precast concrete frame elements originally were designed to span two floors. Whereas the architect preferred to increase the length of concrete elements, the design and construction teams reflected on the structural and constructability aspects of this decision. Involving the project manager, design manager, and construction manager in decision-making enabled to consider a wide range of aspects, including transport and lifting requirements, structural stability, and a safe installation process, in addition to architectural requirements, when specifying the length. The design and construction expertise of these participants, and their understanding of a suitable construction process, which was developed when deciding on the construction methodology, provided a broader view of façade design implications and encouraged discussions about a variety of requirements. Consequently, these participants were able to focus not just on what length was required for the elements, but to understand why the length could not exceed a certain limit, and how the design, construction, and transportation requirements all could be fulfilled. The decision outcome addressed the architectural and transportation requirements, and workers could install the elements and access the connection points safely while standing on the finished floor slabs inside the building.

Opportunities for effective interaction and knowledge transfer are increased when participants with relevant knowledge and expertise are involved directly in making interdependent decisions. Therefore, participants will be able to make more-informed decisions by directly including their tacit knowledge (i.e., the how) and the logic behind the design choices (i.e., the why). In addition, direct involvement increases the frequency of messy talk and spontaneous dialogue among participants about potential design refinements as well as addressing emergent problems and disciplinary conflicts (Dossick and Neff 2011). Dossick and Neff pointed out that these informal direct interactions can increase the exchange of tacit knowledge (which requires more effort to be transferred) and greatly contribute to creativity during the design process.

Implications for Design Management

Design managers have a great influence on the structure and knowledge composition of design teams as well as on team cohesion and its communication environment (Hao et al. 2011). They play an important role in engaging participants with appropriate expertise in design decision-making and facilitating and maintaining effective communication during the design process. Previous research in the project management context suggested that effective communication routines need to enable stakeholder knowledge sharing and involvement to shape the project outcomes (Butt et al. 2016). Furthermore, the evidence from the case analysis in this paper reflects that, underpinning the design decision-making process, there was a strategic tendency to involve relevant project participants and enable them to influence decision outcomes, emphasize and encourage continual improvement of design and construction aspects, and involve suppliers and subcontractors and establish beneficial relationships with them. In particular, the application of the multilevel sociotechnical framework in the case study revealed that reciprocity, transitive closure, and cross-level closure were significant social processes during the design. These results indicated that direct involvement of participants with relevant knowledge in making interrelated decisions and collaborative information exchanges between them were associated significantly with positive design outcomes. The project team was able to consider design, construction, and maintenance requirements, and effectively address the nonroutine design and construction challenges they faced in the project.

The framework can help design management teams to plan, visualize, and monitor design decision-making patterns. The planning of project communication specifically needs to take into account the know-how of project participants (Butt et al. 2016). Application of the framework can help design managers to plan necessary interventions to ensure that interactions between design participants involve the relevant know-how and enable knowledge sharing to generate effective design solutions.

Design complexity cannot be eliminated, and a complex sociotechnical system cannot be controlled fully (Saurin et al. 2013). Nevertheless, the framework proposed in this paper can help design management teams to understand and cope with the sociotechnical complexities of design process. Saurin et al. (2013) proposed a number of guidelines for managing complex sociotechnical systems in organizations: making complex processes and outcomes visible (including informal practices), encouraging diversity of perspectives, complementary expertise and reduction of power differentials when making decisions, anticipating and monitoring the effects of small changes, monitoring and understanding the gap between prescription and practice, and supporting resilience.

By mapping the interdependencies between social and technical elements in the design process, the framework gives visibility to the complexities of the design decision-making, including its formal and informal underpinning interactions. In addition, analyzing the structure of design multilevel network, as undertaken in this paper, reveals the dominant, yet mostly informal, social processes that actively influence decision-making outcomes. Therefore, favorable social processes, such as reciprocity, disciplinary closure, and interdisciplinary knowledge brokerage, can be stimulated in design teams. In addition, by understanding the interdependent design decisions, knowledge requirements can be anticipated, and interventions can be planned to involve the appropriate sources of knowledge and expertise in decision-making at the right time, e.g., by encouraging and empowering relevant participants to participate actively in decision-making. Thus, the diversity of knowledge and perspectives can be enhanced during design and the effects of the interventions can be monitored.

Furthermore, mapping the informal social processes and interactions can reveal gaps between the prescribed formal procedures, imposed by project governance structures, and the practice adopted by participants. Project management teams and disciplinary managers can benefit from this visibility. They can identify and stimulate the favorable informal social processes and practices, for example through granting authority to local team members to engage in informal interdisciplinary interaction and act as boundary spanners when outside knowledge is needed, thus filling the gaps within formal structures during expected and unexpected situations. Such an approach can enhance design team resilience and enable them to adapt better to the changing project environment.

Conclusion

Design decision-making is a complex, interactive and multidisciplinary process. Design decisions emerge during the complex and dynamic social interactions and information exchanges among project participants. In addition, these decisions are the reason for the interactions and influence their patterns. Hence, the social and technical aspects of design process are interrelated.

Despite recognizing this interdependence, previous research has examined the social and technical aspects of the design process separately rather than concurrently. Furthermore, although a network approach has been adopted previously to study social interactions in construction projects, these applications have been single level and predominantly have taken a static and aggregated view of the interactions. Consequently, these studies have not captured effectively the dynamism and true complexity of the sociotechnical context of the construction design process.

This paper makes a methodological contribution to the body of knowledge within construction management by introducing a sociotechnical framework. The framework addresses the gap in previous research by providing a useful and comprehensive theoretical perspective to model and understand the complexities of decision-making in construction projects. It enables researchers and analysts to map and analyze simultaneously the technical dependencies among decisions, social interactions among participants, and participants' influence on decisions. By mapping the structure of design system, the framework helps to provide insights into the system behavior and make improvements while considering the entire system.

The framework enables simultaneously investigating the technical interdependencies among design decisions and the social interactions among participants at different analysis levels. Application of the framework in a case study setting made it possible to investigate several theoretical mechanisms which motivated the emergence of particular network patterns, created an alignment between information exchanges and technical interdependencies of design decisions, and stimulated specific network outcomes. Consequently, knowledge compositions and interactions during the design process were studied within the context of decision-making as opposed to separate from it.

Application of the framework also involved the combination of quantitative and qualitative data for simultaneous consideration of decision-making and social interaction patterns. The pattern of interdependencies was analyzed using multilevel exponential random graph models. Hence, it was possible to investigate the building blocks of the network and understand how social processes (such as reciprocity and closure) at a local level give rise to emergent global interaction patterns, thus establishing a link between local and global patterns and characteristics. Moreover, it was possible to understand whether the interactions among participants in this case effectively enabled the required information exchanges and matched the decision interdependencies and complexities.

An understanding of the sociotechnical characteristics of decision-making in construction projects makes two advances possible. First, improvement efforts can be integrated into decision-making activities effectively and proactively. Second, relevant knowledge and expertise can be made accessible and used within interaction networks that underpin specific decision-making situations.

There are some limitations. First, a single case-study project was presented in this paper. Because the purpose of case study was to indicate the application of the framework, only one case was presented; however, the framework actually was applied in six case studies, reflecting its robustness. Although this paper showed that the framework can be applied to investigate the sociotechnical complexities of decision-making in projects, it is acknowledged that the case study results cannot be generalized to all construction projects, particularly those procured using different project delivery mechanisms. Second, the study focused only on technical design decision-making and the participants who were involved in it. It is recommended that future studies apply the framework to investigate decision-making more comprehensively over the project life cycle. Another limitation is the retrospective nature of data collection. Consequently, there was a reliance on participants' ability to recall the decision-making process and the extent to which they interacted with other project participants. However, conducting multiple interviews with participants from different organizations and roles, and confirming the decision-making process and the existence of interactions ties helped to overcome the problems inherent in this bias. Although using alternative data sources, such as email communication, can help address the potential recall bias, they limit the ability to capture communication comprehensively, particularly during face-to-face meetings and informal conversations, which are essential for design decision-making. To overcome the study limitations, future research may consider longitudinal and prospective data collection in live projects over their life cycle. Applying the framework in multiple project settings can reveal more comprehensively the features of effective interaction in the context of construction design.

Data Availability Statement

Interview data collected during the study are proprietary and confidential in nature and may be provided only with restrictions to protect participants' identity.

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