A MULTI-LEVEL AND IN-DEPTH ANALYSIS OF AEC PROJECT NETWORKS: TOPOLOGY, SOCIAL INFLUENCE, AND INTERVENTION

By

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ABSTRACT

Architectural, Engineering, and Construction (AEC) project teams comprise a diverse set of individuals and organizations that work under pressure to execute a project. Efficient collaboration and integration are vital to generating and conveying the necessary expertise for optimized solutions and project performance. However, the transient and fragmented nature of the AEC teams poses a challenge to collaborate efficiently and impacts the project performance adversely.

This dissertation examines the project networks that allow actors to create and channel expertise that can be used to enhance project outcomes including sustainability for AEC projects. To achieve the study goal, longitudinal data are collected from an AEC project team with more than 1000 team members. The data are analyzed using mixed methods and Social Network Analysis (SNA).

This research consists of three main independent but interwoven parts: (1) Part 1 examines the topology and evolution of AEC project team collaboration networks that facilitates expertise flows for optimal sustainability outcomes; (2) Part 2 examines social influence mechanisms and how individuals change knowledge-sharing behaviors in project networks; and (3) Part 3 develops an intervention protocol for AEC project teams to find appropriate solutions for network constraints and improve knowledge transfers for optimized project performance.

The study's main contribution to the body of knowledge is providing a holistic and systematic evaluation of AEC project networks with special consideration to their dynamic and multi-level characteristics to improve the project outcomes, particularly sustainability. First, project networks have unique needs that cannot solely be explained with network metrics. This study fills the gap by explaining desirable network topologies and how to achieve them for

enhanced project outcomes. Second, the study establishes a social influence model to understand conformity and influence processes in project networks and enable the diffusion of necessary behaviors for better project performance. Finally, the study provides an intervention framework for AEC teams in selecting and assigning experts in projects as well as managing team communications and networks in a dynamic manner during project delivery for better system functioning and resilience.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AEC	Architectural, Engineering, and Construction
SNA	Social Network Analysis
LEED	Leadership in Energy and Environmental Design
PDM	Project Delivery Method
CMAR	Construction Management at Risk
SD	Schematic Design
DD	Design Development
CD	Construction Documents
IRB	Institutional Review Board
MSU	Michigan State University
EA	Energy and Atmosphere
MEP	Mechanical, Electrical, Plumbing
IEA	International Energy Agency
RFI	Request for Information
AIA	The American Institute of Architects
EAI	Energy Information Administration
USGBC	The United States Green Building Council
RIR	Robustness of Inference to Replacement

1 OVERVIEW OF THE RESEARCH

1.1 Background

Architectural, Engineering, and Construction (AEC) project teams consist of individuals not only from different expertise areas but also with varied motivations and backgrounds operating under pressure to deliver a project (Garcia et al. 2020; Mollaoglu-Korkmaz et al. 2013). Effective collaboration and integration are vital to generating and conveying the necessary knowledge for optimized solutions and project performance (Kratzer et al. 2010). However, due to the transient and complex features of AEC projects, experts often fail to collaborate efficiently and benefit from each other's expertise and the AEC industry seeks remedies to overcome these challenges (Du et al. 2020).

Traditionally, the construction industry has measured performance with the technical aspects of projects such as enhanced quality, time, and cost efficiency (Chinowsky et al. 2008). In recent years, sustainability has become an emerging concept and performance indicator in the AEC industry as a solution to environmental problems, such as depletion of energy and resources and increasing pollution (LEED 2016). However, the unique nature of sustainable buildings brings additional complexity, which requires diversely skilled team members to coordinate for acquiring collective knowledge and synchronizing efforts for innovative solutions (Jones et al. 1997; Korkmaz et al. 2010; Riley et al. 2004).

The literature has focused on the following aspects to achieve team integration: (1) organizational metrics with project delivery methods (PDM) such as the timing of involvement, leadership, and owner commitment (Bilec and Ries 2007; Mollaoglu-Korkmaz et al. 2013; Raouf and Al-Ghamdi 2019) (2) knowledge transfer practices (Garcia and Mollaoglu 2020; Javernick-Will 2012; Sun et al. 2019) (3) social and motivational factors such as shared values and trust

(Chinowsky et al. 2008; Chiocchio et al. 2011; Moore and Dainty 2001) and (4) information technologies to foster collaboration (Al Hattab and Hamzeh 2018; Du et al. 2020).

In the last decade, network analysis has become of growing interest in the AEC domain, particularly for the evaluation of team integration, communication, and knowledge sharing (Chinowsky et al. 2008; Kereri and Harper 2018). Topologies of collaboration networks can provide insights into expertise flows occurring to create collective outputs and complete tasks (Chinowsky et al. 2008), emergence and evolution of teams (Lin 2015), individuals' influence and impact over the network (Frank and Fahrbach 1999; Kereri and Harper 2019), and collaboration problems and potential remedies (Cross et al. 2002).

However, construction teams are dynamic and organizational structure is not enough to understand project networks due to the emergent communication patterns during project delivery (Cross et al. 2002; Franz et al. 2018). Thus, a longitudinal and multi-level analysis of AEC collaboration networks is necessary to understand what network characteristics are favorable for project outcomes, how project networks evolve during project delivery, how team members influence each other, and how collaboration networks can be leveraged to better enable expertise flows. (Foss et al. 2010; Garciacortes 2017).

1.2 Problem Statement and Gaps in the Knowledge Base

Several studies have investigated AEC collaboration networks and the effect of network features on project outcomes. However, there is still a need for a more holistic and systematic approach that considers the dynamic and inherent features of project delivery stages to address the gaps in the knowledge base.

Gap #1: *There is a lack of longitudinal evaluations of project network topologies and expertise flows at multi-levels (i.e., individual, sub-team, and team levels). The need and* *the gap manifest themselves especially in the context of sustainability, as sustainable buildings require additional considerations due to the need for highly optimized systems and interdisciplinary collaboration.*

Via SNA, team characteristics and interactions can be mapped, visualized as sociograms, and mathematically assessed by using network metrics (Hanneman and Riddle 2005). The literature offers metrics to evaluate and interpret the structural properties of AEC project networks, such as density, triadic closure, degree centrality, betweenness centrality, and tie strength, which have been reported to influence sustainability outcomes (Henry and Vollan 2014; Schröpfer et al. 2017).

However, the impact of structural network metrics on sustainability outcomes depends on network dynamics, such as trust or values (Chinowsky et al. 2008), network context and team structure (Cross et al. 2002), resources flowing in the network, and priorities (Henry and Vollan 2014). Therefore, studying the topology of interactions between components of a network is also important to interpret the meaning of collaboration patterns (Albert and Barabási 2002). Examining the way nodes are placed and interconnected might shed light on sustainability problems. For example, even if a network has the desired metrics, the lack of expertise diversity may hinder its ability to solve sustainability problems (Henry and Vollan 2014). Similarly, boundary spanners bring external valuable information into their team and enhance the efficiency of knowledge exchanges across organizational, hierarchical, or expertise boundaries (Cross and Prusak 2002; Iorio et al. 2012). For instance, a redundant connection in a network may not be as important as a boundary-spanning tie. Therefore, there is a need for holistic evaluations and understanding of complex, multi-level AEC project networks utilizing longitudinal and in-depth reviews of network topologies in the context of sustainable AEC projects.

Gap #2: *There is a need to understand influence mechanisms and how team members modify their attitudes and actions in project teams, especially relating to sustainability knowledge exchanges.*

Project teams are complex involving individuals from different expertise areas and organizations, usually with no previous experience (Garcia et al. 2020). These experts can fail to collaborate efficiently and benefit from each other's expertise (Mollaoglu-Korkmaz et al. 2013). Highly integrated project teams succeed in overcoming these challenges by engaging in cross-level, cross-domain, and cross-organization knowledge transfers (Garcia et al. 2021). Knowledge transfer involves continuing social interactions between project team members, leads to certain behavior patterns (Nonaka 1994), and results in social influence as a result of conformity pressures (Cialdini and Goldstein 2004; Frank et al. 2004; Rogers et al. 2014).

According to the Social Influence Theory, individuals change beliefs and behaviors as a result of exposure to information or sentiments of the actors they interact with (Kaufer and Carley 2012). By enabling and catalyzing certain interactions, influence and dissemination of desired practices might be facilitated to achieve optimized project outcomes. However, it is not clear how individuals are influenced in project teams relating to sustainability knowledge exchanges. Especially, how social interactions at the project level influence the way individuals transfer knowledge at the group level within projects is yet to be explored.

Network properties of the surrounding nodes affect the attitudinal and behavioral responses of the actors (Pauget and Wald 2013). Therefore, it has been suggested that structural properties of networks are appropriate in measuring influence occurring (Brass 1984). In particular, influence in a network has been associated with the centrality of an actor in a network, as centrality reflects an individual's power, status, or importance (Brass 1984), and the importance of nodes in a network diffuse to the nodes that they are connected to (Golbeck 2013). Understanding structural and social mechanisms in networks is critical to enhancing necessary coordination and diffusing desired practices in pursuit of optimized project outcomes.

Gap #3: *There is a lack of a systematic review of project network topologies and features to develop interventions that can potentially increase expertise flows, improve system functioning and resilience, and help improve project outcomes.*

The network intervention term describes the procedure of using SNA to generate social influence, promote behavior change and improve performance (Valente 2012). However, is a lack of intervention studies across project network domains that can help improve the functioning of project team networks (Matous et al. 2021). Especially, this gap is wider for AEC project teams, where special considerations exist for network interventions.

1.3 Research Goal and Objectives

The overall goal of this research is to develop a holistic understanding of AEC project social networks that allow actors to generate and channel knowledge that can be used to optimize outcomes including sustainability for AEC projects. This study extends the previous studies by examining project networks longitudinally at different phases of the project delivery at multi-levels using SNA bolstered by mixed methods Figure 1-1.

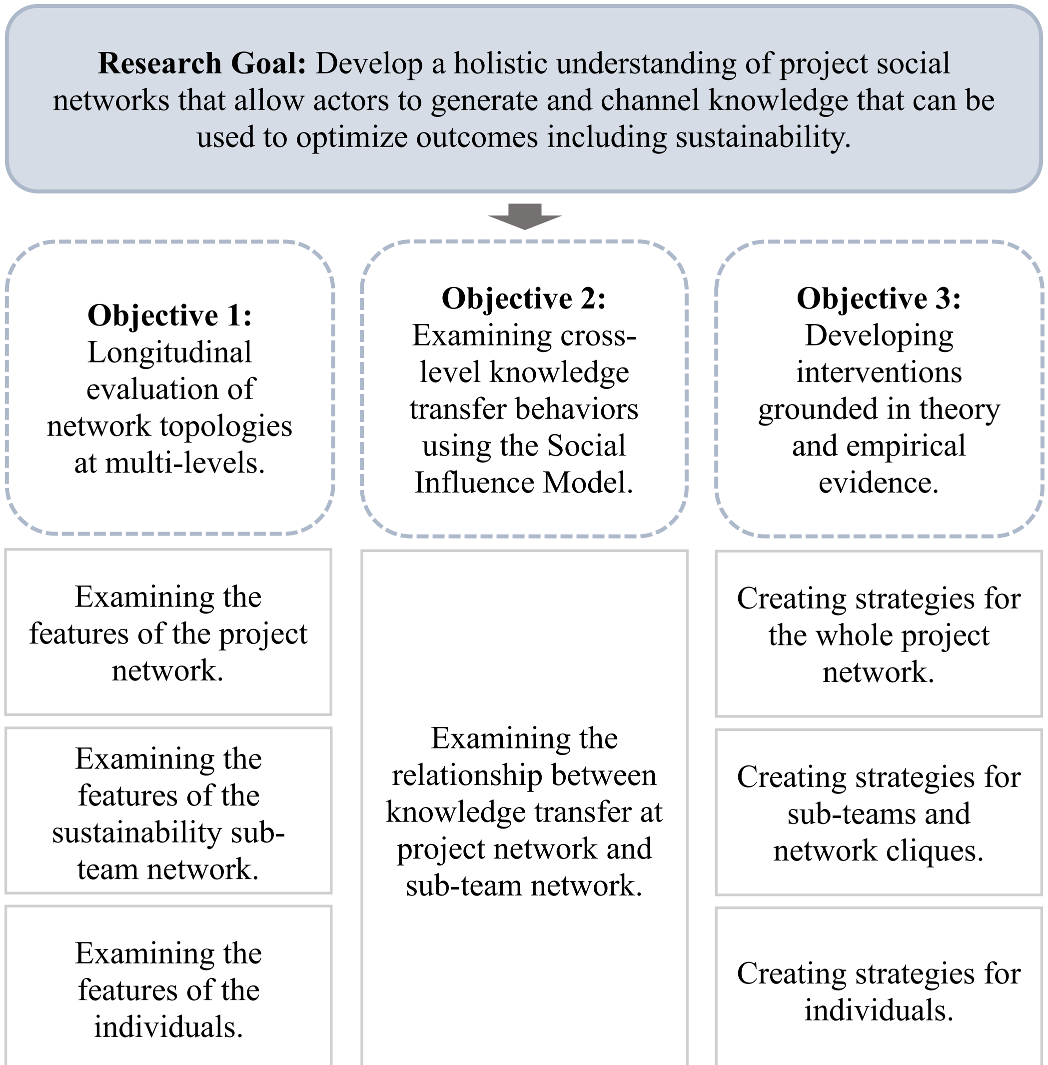

Figure 1-1. Research goal and objectives

Based on the problems stated earlier, the objectives of this research are as follows.

Objective 1: *Evaluate the emergence and evolution of a project's network during project delivery at multi-levels and identify the network characteristics that allow experts to exchange knowledge to optimize sustainability outcomes for AEC projects (Chapter 2).*

Objective 2: *Examine the changes in knowledge transfer behaviors for sustainability in project teams using influence model and establish a quantitative model to understand how* *project-level knowledge transfer, including all team members from all groups, influences group-level knowledge transfer in complex project collaborations (Chapter 3).*

Objective 3: *Conduct a systematic review of performance and communication trends of AEC projects to develop a rigorous intervention protocol grounded in theory and empirical evidence that can potentially increase expertise flows and system resilience and help improve project outcomes (Chapter 4).*

1.4 Research Structure

1.4.1 Main Methodology: Social Network Analysis

Network theory is a body of principles that explains the interactions between actors within a network. A network shows different kinds of relationships and is derived from relational data between people, organizations, or brain cells (Kadushin 2012). Developed by (Moreno 1934), social network analysis is the process of evaluation and measurement of relational and social structures (Butts 2008; Moreno 1960). The simplest network called "dyad" consists of two basic elements, two individuals (nodes, vertices, etc.), and one relationship (edge, link, etc.) connecting them. Larger networks are mainly represented with sociograms, which are the maps in which we visualize the relationship patterns of actors in a network (Hanneman and Riddle 2005). Since social networks consist of more than two nodes, some concepts and metrics are needed to interpret the data shown on sociograms.

The literature offers metrics to evaluate the structural properties of sociograms. Based on previous studies, those properties are classified according to levels of analysis: (1) Network-Level (global), and (2) Node-Level (local) metrics. Network level metrics are density, structural holes, cohesiveness, triadic closure, and individual-level metrics are centrality and tie strength.

Additionally, SNA can be conducted at the sub-team level to analyze the assigned or emerging clusters of nodes with distinctive features within a network (Duva et al. 2020; Steketee et al. 2015).

Density is a measure of the whole network and is calculated by dividing the number of existing ties by the number of all possible ties. Therefore, density is supposed to be between 0 and 1. Literature suggests that higher density means more interaction and information exchange between actors and therefore enhances outcomes. However, if the links do not contain positive feelings, such as friendship and trust, then less dense (sparse) networks are preferable (Henry and Vollan 2014). *Structural holes* in a network are based on a gap between two nodes or groups. A bridge is very important because it is the only actor that connects two clusters and transfers the information between them (Burt 2004). *Cohesiveness* is a measure of the extent to which actors in a network are directly linked to each other. Moody and White (2003) define cohesiveness as the number of social relations among the network members that hold the network together and add that it is equal to the minimum number of nodes who disconnect the group if eliminated from the network. *Triadic closure* indicates that if A-B and A-C nodes in a network have a relationship, it is most likely that B-C will have at least a weak tie as well (Granovetter 1973). Although triadic structures strengthen trust and collective action, they can create a lack of diversity, which might inhibit the ability to solve problems (Henry and Vollan 2014).

Centrality is a measure of individuals and defines the most important or central nodes in a network. In a network, the nodes with the highest centrality can control expertise flows and affect the diffusion of information. There are different centrality measures proposed depending on the definition of importance (Borgatti 2005). The most important centrality measures are degree centrality, closeness centrality, betweenness centrality, and eigenvector centrality (Bonacich 1972; Freeman 1978). *Degree centrality* is determined by the degree of a node, which is the number of other nodes linked to it (Freeman 1978). In an n-node network, the maximum degree of a node is (n-1). The nodes connected to a particular node are impacted by the source first, therefore degree centrality can be regarded as a measure of immediate influence (Borgatti 2005). *Closeness centrality* emphasizes the distance of a node to all other nodes in a network and is calculated as the sum of the length of the shortest paths between the node and all other nodes in the graph (Freeman 1978). For expertise flows, nodes with low closeness are considered well-positioned to receive the novel information on time (Borgatti 2005). *Betweenness centrality* is calculated with the number of times a node acts as a bridge along the shortest path between two other nodes (Freeman 1978). In the case of expertise flows, when more people depend on a node to connect other people, more control and power that node gain over the flows (Borgatti 2005; Hanneman and Riddle 2005). *Eigenvector centrality* is calculated based on the influence of a node in a network and it depends on the number of neighbors and quality of its ties. In other words, if a node is connected to many nodes with high eigenvector scores, that node's score is high, too (Bonacich 1972). Therefore, the eigenvector centrality measure is ideal for social influence processes (Borgatti 2005). *The strength of a tie* is the "combination of the amount of time, the emotional intensity, the intimacy, and the reciprocal services" (Granovetter 1973). Even though stronger ties are considered more important in the literature, weak ties are important as well due to their features. They connect people from different social circles, aid the flow of novel information and act as a bridge (Granovetter 1973).

Lastly, a group of nodes with distinctive features in a network can cluster together and form special network configurations such as subgroup structure or core-periphery structure. In a core-periphery structure, the core, a small number of frequently interacting members, forms the center of the network, whereas the periphery surrounds the core with limited connections to them

(Borgatti and Everett 2000). Subgroup structure represents the existence of groups of individuals, who are densely connected within their group while being loosely connected to other groups (Frank 1995).

1.4.1.1 Social Influence Theory

Social Influence Theory proposes that individuals change their beliefs and attitudes through interactions with others (Kelman 1953). They begin with initial opinions and reform their beliefs, attitudes, or actions in reaction to the people they connect with (Frank et al. 2018; Marsden and Friedkin 1993). The diffusion and adoption of new practices, ideas, or behaviors do not transpire without influence (Kadushin 2012).

In project teams, influence follows the dissemination of information (Li et al. 2018) after two individuals attempt to solve a problem by collaborating at the dyad level (Poleacovschi et al. 2017). Therefore, it is important to examine knowledge transfers at individuals' level to get an insight into how organizations function (Foss et al. 2010; Javernick-Will 2012), as basic influence processes yield complex interaction and behavior patterns at sub-team and network-level (Frank and Fahrbach 1999; Friedkin and Johnsen 1990).

1.4.1.2 Social Network Analysis in the AEC Literature

In recent years, there is an exponential trend in the number of SNA studies in the AEC domain (Kereri and Harper 2019). The topic has become of growing interest, particularly for the evaluation of team integration, communication, and knowledge sharing (Kereri and Harper 2018). Similarly, in their research Zheng et al. (2016) underline the growing interest in SNA in the AEC domain and present that most papers were published on performance and effectiveness, communication and coordination, and knowledge management.

SNA studies in the construction domain are mainly concerned about communication and collaboration among parties and their impact on performance because different individuals and companies working toward a common goal enter and exit the project network (Lin 2015). Even though there is a growing interest for SNA in the construction domain, there is still a gap between the features of project networks and optimizing project outcomes. This gap is even bigger for sustainable project delivery as the number of actors and systems needed is greater compared to conventional construction projects.

1.4.2 Data

To achieve the goals of this research, I have collected data from a major institutional renovation project located in a Midwest state in the United States. The project started in December 2018 and ended in December 2020 and spanned around two years. The project budget was $22 million, and the delivery method was Construction Management at Risk (CMAR). The project team consisted of over 1000 individuals including the owner's representatives, architects, engineers, contractors, subcontractors, and consultants with different levels of expertise. Various types of data were collected as follows:

1. Archival data
    - Archival data included the meeting minutes and project documents shared with all project team members on web-based platforms and aided the creation of a framework for data analyses, determination the sub-team network members, and performance calculations as discussed in the section below.
2. Email exchange data
    - Email exchange data were the main source to examine the collaboration networks and were collected with the help of the project owner, designer, and general contractor. The

e-mail exchange data consisted of the e-mail headers (i.e., sender, receiver, time, and e-mail subject) without the email content and were collected in two steps: (1) Primary email exchange, (2) Secondary email exchange. Primary email exchange data were collected with the help of the owner's IT department. It consisted of the emails between the owner and two other main organizations: architectural designer and general contractor. The owner's IT department could extract emails that included at least one individual from the owner's organization per email. Emails that did not include anybody from the owner's team could not be captured by the owner's IT, as they did not belong to the owner's server. Therefore, our research team went one step further and collaborated with the architectural designer and general contractor to get the secondary emails. Those secondary emails might be between 1: The individuals from the architectural or construction management team 2: Between one of those parties and their subcontractors, consultants.

3. Observational Data

    - Two coders from our research team observed the weekly project team meetings for almost two years. The data collected through observation provides flexibility and insight, as the researcher can observe all interactions (Wimmer and Dominick 2013).

The coders recorded the number of "information given", "information asked" and "other information" by each individual by using Microsoft Excel spreadsheets in the meetings and coded the conversation row by row. Each row was assigned to a piece of information provided by a person, once the person changed or the same person provided another piece of information, the coders stepped into the next row. This was helpful to track the sequence of the conversations as well (i.e., the letters in the figure indicate the sequence of the conversation). After transcribing the conversation in the meetings, the coders assigned blue, red, and gray colors for “information given”, “information asked” and “other information” respectively. Excel macros were used to calculate the amount of information in each category as seen in Figure 1-2 below. To maintain inter-coder reliability, (1) after each project meeting coders came together to compare and combine notes and (2) calculated the rank Spearman correlation using their records for each individual observed in project meetings. The average Spearman rank correlation was around $r = 0.89$, $p < .01$ indicating that, overall, coders’ perceptions were similar in how active each participant was in project meetings as compared with their peers. Final merged observational data were used as a node attribute for individuals in sociograms as the people who gave more information in the team meetings were represented with a bigger dot.

Meeting on: Date - Coder: A

Legend	Person 1	Person 2	Person 3	Person 4	Person 5	Topic Discussed	
Give Informa	2	0	1	2	1		
Ask Informat	1	0	1	1	1		
Other	0	1	0	1	0		
Total	3	1	2	4	2	ID	Description
.	a					1	Cost Estimate
.		b				1	Cost Estimate
.	c					2	Scheduling
.			d			3	Architectural Layout
.				e		3	Architectural Layout
.					f	3	Architectural Layout
.				g		3	Architectural Layout
.			h			3	Architectural Layout
.				i		3	Architectural Layout
.	j					3	Architectural Layout
.					k	3	Architectural Layout
.				l		3	Architectural Layout
.							

Figure 1-2. Observational data coding

4. Survey Data

- Project team members were asked to fill out surveys three times during the project delivery and evaluated the performance of their peers, sub-teams, and team through questions relating to contribution to project execution, communication and coordination skills, adaption to changes, and innovation. Surveys included demographic questions such as experience in the AEC industry and with similar projects, areas of expertise, and education level to gain further insight into the project network (Appendix A- Surveys).

5. Interview Data

    - To enable data triangulation and improve research quality, I interviewed project participants and verified that the sociograms developed using email data are representative of their communication patterns. Moreover, interviews also helped vetting the study findings and developed intervention strategies (Appendix A-Interview).

1.4.3 Analysis Methods

1.4.3.1 Qualitative Methods

AEC project delivery is a dynamic process consisting of cyclic phases, namely progress loops, where each phase becomes the input for the succeeding phase during project delivery analyses (Garcia et al. 2014; Marks et al. 2001). An AEC project goes through Schematic Design (SD), Design Development (DD), Construction Documents (CD), and Construction episodes. Additionally, depending on project progress, a project may have many more milestones and episodes can be broken down into shorter time intervals. I analyzed archival documents to determine the projects' progress loops (i.e., episodes and monthly time intervals) to create a framework for the analyses. All dissertation chapters use progress loops to observe and scrutinize project networks longitudinally, since progress loops specify and distinguish the project needs, responsibilities of teams, and communication patterns.

Archival documents also aided performance calculations, which were used as an indicator of project performance. Using project meeting minutes, the research team created a Gantt chart to track issues over time and calculated project performance using the percentage of total project issues resolved out of ongoing ones in a given time interval.

1.4.3.2 Social Network Analysis

The SNA software Gephi, UCINET, and KliqueFinder were used to examine the communication dynamics between project team members from different perspectives, generate sociograms, and calculate network metrics. Email exchange data were the main source for SNA. To determine the strength of ties between nodes, we assigned 3, 2, and 1 as weights for daily, weekly, monthly communication, respectively. Individuals were coded according to: (1) Main roles in the project (i.e., owner, designer, contractor); (2) tiers of decision-making and operation (Mollaoglu-Korkmaz et al. 2014) and (3) expertise areas such as organizational planning and programming, project planning, project needs, and program, management, architectural design, civil engineering, mechanical, electrical and Mechanical, Electrical, Plumbing (MEP) construction (Garcia et al. 2020). Observational data were used as a node attribute on sociograms (i.e., give information during project team meetings).

1.4.3.3 Influence Model: Regression Analysis

Influence occurs as a result of an interaction (e.g., email exchange) between two people (Freeman 1984). We use the influence model below adopted from Frank and Fahrbach (1999) and Marsden and Friedkin (1993), in which the influence is a function of exposure of i to the attributes of j through interaction:

$$y_{it1} = \rho \sum_{j=1}^{n} \left[w_{ij(t0 \rightarrow t1)} z_{j(t0)} \right] + \gamma y_{it0} + e_{it}$$

y_{it1} — Outcome. An attitude or behavior of actor *i* at time t_1

ρ and γ — Influence coefficients

$w_{ij(t0\rightarrow t1)}$ — Interactions received by *i* from *j* during the period of t_0-t_1

z_{jt0} — An attitude or behavior of actor *j* at time t_0

$\sum_{j}^{n} w_{ij(t0\rightarrow t1)} z_{j(t0)}$ — Exposure, indicating potential influence of *j* on *i* during the period of t_0-t_1

y_{it0} — An attitude or behavior of actor *i* at time t_0

e_{it} — Error term

1.4.4 AEC Project Delivery and Research Design

Figure 1-3 explains the overall research design. Briefly, this research attempts to answer three questions relating to project networks: (1) Which network characteristics are desirable for sustainability outcomes; (2) How influence occurs in a network; and (3) What are the steps of developing a rigorous intervention protocol? Even though each chapter is independent, they are interwoven with each other for the holistic evaluations of project team networks.

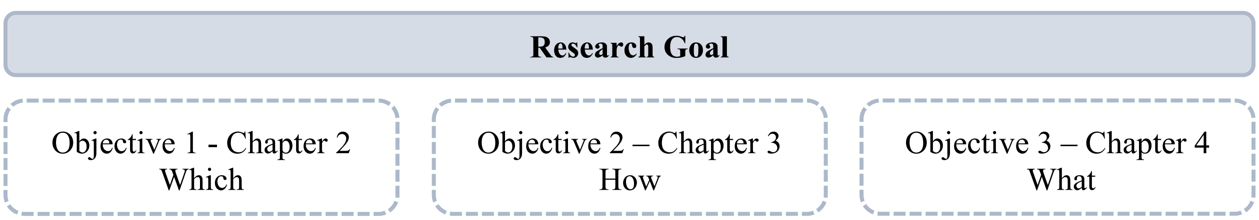

Figure 1-3. Dissertation structure

Chapter 2 aims to achieve objective 1. Below are the steps of the chapter 2:

- Review existing literature on sustainability and AEC project networks to derive the network metrics that potentially impact sustainability outcomes.
- Determine the sustainability sub-team network boundaries focusing on the individuals working on Energy and Atmosphere (EA) issues. Similarly, find the performance of the EA team using issue resolution rate for each interval.

- Create sociograms longitudinally for each time interval for the whole team and EA sub-team to compare and evaluate networks at both levels. Calculate network metrics for the EA sub-team.
- Evaluate the relationship between the EA sub-team network metrics, topology, and performance.

Chapter 3 aims to achieve objective 2. Below are the steps of the chapter 3:

- Review existing literature on influence theory and find the network metrics that can be used as a proxy for knowledge transfer behaviors.
- Generate sociograms and conduct project-level SNA for each episode using e-mail data and calculate the network metrics.
- Generate sociograms and conduct sub-team level SNA for EA sub-team for each episode using e-mail data and calculate the network metrics.
- Evaluate the influence occurring across-levels and quantify the changes in knowledge transfer by using the network analysis results from above steps.

Chapter 4 aims to achieve objective 3. Below are the steps of the chapter 4:

- Review existing literature on network interventions and potential intervention frameworks.
- Evaluate the performance and communication trends in the light of intervention framework to find trends, ups and down of the project delivery by considering the special features of AEC project networks.
- Develop intervention framework for AEC teams.
- Conduct interviews for vetting the developed strategies and refine and revise if needed.

1.4.5 Institutional Review Board Approval

Since this study involved human subject data, getting Institutional Review Board (IRB) approval was compulsory. Therefore, a study protocol was prepared and submitted to the IRB at Michigan State University (MSU) (Appendix A). The protocol included details about data collection and data analysis procedures. After getting the IRB approval letter (Appendix B), data collection started with the recruitment of human subjects. Individuals, who are key to the project, such as project managers, designers, and owner's representatives, were asked to sign a generic and extensive consent form, which included all steps of the study including surveys, interviews, interventions, collaboration to collect archival, observational and email data. Secondary people, mainly from tier 3, were only asked to fill out the surveys. Therefore, those people got the consent form at the beginning of the online surveys. All consent forms included details about the research objectives, potential benefits and risks, privacy and confidentiality issues, and their rights to participate or withdraw. Moreover, the contact information of the author, dissertation committee members, and IRB at MSU were added in case the project participants had any concerns or questions (Appendix C).

1.5 Research Quality

Reliability and validity are two concepts used to assess the robustness and quality of research. They are the indicators of how well a method or technique measures what the researchers wanted it to measure. Reliability is concerned with the quality of the method or procedure, whereas validity is concerned with the quality of study results. To ensure validity, reliability is a must, but not the other way around (Wimmer and Dominick 2013).

1.5.1 Reliability

Reliability refers to the extent to which results are consistent over time. A research method is reliable if the same results are produced every time under the same conditions (Joppe 2006). For the surveys, I conducted pilot surveys to ensure the survey questions are clear and everyone interprets the questions similarly (Singleton Jr and Straits 1999). For the intercoder reliability, Spearman rank was calculated. The average Spearman rank correlation was $r = 0.89$, $p < .01$ indicating that, overall, coders' perceptions were similar in how active each participant was in project meetings as compared with their peers. As a rule of thumb, reliability is good if Spearman Rank is equal or greater than 0.7.

1.5.2 Validity

Validity is the second measure to assess if a method or test is measuring what it is supposed to measure (Wimmer and Dominick 2013). Construct and internal validity refers to the control over research conditions and eliminating the artifacts (confounding variables) to avoid making incorrect explanations for the results (Wimmer and Dominick 2013). Construct validity is a measure of data collection phase, whereas internal validity is about data analysis. Construct and internal validity of this research were achieved by the triangulation of methods (e.g., mixed methods and SNA), data (e.g., interviews, observation, archival, and email data) and investigators (e.g., two observes attending weekly project meetings to collect ethnographic data) (Denzin 2007). Moreover, definitions and measurements for study variables were developed based on the literature. Pilot surveys were sent to implement necessary modifications.

External validity refers to the extent to which the study results are generalized "across different populations, settings, and time" (Cook and Campbell 1979). Selecting a sample, which represents the group to which the results will be generalized improves the external validity (Cook and Campbell 1979). Even though the focus of this research is AEC teams, the research is built upon research findings and theories from different disciplines such as social networks, sociology, organizational science, and construction management. In other words, a comprehensive literature review was conducted to ground the hypotheses of this study by using sources from different domains including but not limited to Journal of Green Building, American Journal of Sociology, Journal of Management in Engineering, Journal of Information Science Engineering, Construction and Architectural Management, Social Networks. Hence, the study findings will be generalizable to the other industries other than the AEC industry in which there are temporarily formed, complex, and inter-organizational project teams to achieve specific goals in a limited time.

1.6 Scope and Limitations

The scope of this study is a medium-size inter-organizational AEC project team delivering an institutional project via CMAR. Therefore, the main limitations of this research include the case study project's teams' size, complexity, and adopted PDM. Therefore, comparisons with smaller or greater teams and project teams developing simpler or more complex designs or implementing different PDMs could not be empirically analyzed, and outcomes are not generalizable. Limitations for each objective and research question will further be discussed in the relevant chapters.

1.7 Deliverables/Research Contributions

The primary deliverable of this project is the development of a holistic understanding of project social networks that allow actors to generate and channel knowledge that can be used to optimize project outcomes including sustainability. Additional deliverables of the research are as follows:

1. Literature review for network theory and SNA for AEC project teams, and theoretical discussion on how network metrics and topologies impact sustainability performance of projects during different phases of project delivery.
2. Establishing a social influence model to understand cross-level knowledge transfer in project networks with a focus on sustainability and identify the relationship between the social network metrics and how network actors get influenced as a result of their interactions.
3. Review of relevant literature on network interventions and develop a network intervention protocol by considering the special features of AEC projects to increase expertise flows, collaboration, and coordination.
4. Theoretical and methodological implications of social networks in inter-organizational and inter-disciplinary project teams.
5. Practical applications of social networks for different organizations and roles in the AEC industry to improve project outcomes.

1.8 Summary

In this chapter, firstly, the gaps in the knowledge base were identified, and the overall goal and objectives of this research were defined. Starting from the research objectives, the research design and structure were explained. Secondly, the data collection and the analysis methods to be used in this research were elucidated. Finally, quality, contribution to the body of knowledge, and the limitations of this research were discussed. More details regarding literature, data collection, and analyses will be studied in the relevant chapters.

2 MAPPING THE TOPOLOGY OF EXPERTISE FLOWS IN SUSTAINABLE PROJECT NETWORKS

2.1 Abstract

Architectural, Engineering, and Construction (AEC) project teams adopt different methods to facilitate collaboration to achieve sustainability goals, which requires a high level of expertise integration. The social network approach addresses the integration and expertise flow dynamics in project networks, which can impact the capabilities and performance of project team members. However, there is a knowledge gap regarding what network characteristics are favorable for improved sustainability outcomes in AEC projects, how they evolve during delivery, and how relevant expertise flows through project networks. To respond to the need in the literature, this study aims to develop a holistic understanding of AEC project team networks and associated characteristics that allow experts to exchange knowledge to optimize sustainability outcomes for built environment projects. We longitudinally collected e-mail exchange, observational, and archival data during the design phase of an AEC case study project and performed Social Network Analysis (SNA) bolstered by mixed methods. Results showed that there is no evidence of relationship between network metrics and performance and network topology matters for AEC project teams. In other words, understanding the interactions between components of a network (e.g., expertise exposure, expertise areas represented in the network and the number of boundary spanners) is important for better sustainability outcomes.

2.2 Introduction

Energy demand and environmental problems arising from buildings and construction activities continue to increase (IEA 2022). With the upward trend in the scenario, stakeholder expectations have increased and new goals have been set to achieve sustainable and energy-efficient building stock (European Commission 2021). Therefore, traditional success criteria for AEC projects, such as time, cost, and quality, have increased to a new level (Chinowsky et al. 2008) and sustainable buildings have grown in importance (LEED 2016).

However, sustainable and energy-efficient projects are complex in nature due to the need for the optimization of complex systems and high-tech components (Rohracher 2001). A high level of expertise integration and collaboration is needed for enhanced outcomes, which is a dilemma for the highly fragmented and traditional architectural, engineering, and construction (AEC) industry (Korkmaz et al. 2010). Until now, the literature has focused on the following aspects to address the challenges of complexity and achieve integration for sustainability goals: (1) organizational metrics with project delivery methods such as the timing of involvement, leadership, and owner commitment (Bilec and Ries 2007; Mollaoglu-Korkmaz et al. 2013; Raouf and Al-Ghamdi 2019), (2) using information technologies such as BIM to foster collaboration (El-Diraby et al. 2017; Harding et al. 2014), (3) and, social network analysis on knowledge transfers in sustainable project teams (Schröpfer et al. 2017).

Social network analysis (SNA) is a systematic way of investigating relational structures (i.e., ties) between a set of actors (i.e., nodes) and visually representing on sociograms (Hanneman and Riddle 2005). The topic has become of growing interest in the AEC domain, particularly for the evaluation of team integration, communication, and knowledge sharing (Kereri and Harper 2018). Moreover, social networks play an important role in accelerating behavioral changes to improve organizational efficiency and diffusion of innovations (Valente 2012) and therefore, achieving sustainability goals (Henry and Vollan 2014).

However, construction teams are dynamic and evolutionary over the course of projects as different individuals and companies come and go based on the project needs and schedule (Lin

2015), and evaluating the social networks based solely on the organizational structure is not adequate to understand the expertise flow patterns (Cross et al. 2002). Thus, longitudinal and multi-level analysis of network topology (e.g., across individual, sub-team, and team levels) is necessary to understand network evolution, expertise flows and promote organizational efficiency for achieving sustainability goals (Foss et al. 2010; Garciacortes 2017).

To address this gap, this study aimed at developing a holistic understanding of how sustainability knowledge transfer networks evolve and allow experts to exchange knowledge that can be used to optimize sustainability outcomes for AEC projects. Specifically, this study explored the social network characteristics of an AEC project team that facilitates expertise flow for optimal sustainability outcomes. The research team longitudinally collected archival, e-mail exchange, and observational data during the delivery of an AEC case study project and performed SNA bolstered by quantitative and qualitative analyses. The sustainability outcomes of the project were evaluated focusing on the Energy and Atmosphere (EA) issues in the project and how they got resolved over time as the most important category based on the highest possible points on Leadership in Energy and Environmental Design checklists (LEED 2016).

2.3 Literature Review

Numerous studies revealed that network structures affect expertise flows needed for coordination (Reagans and McEvily 2003) and different network structures serve different purposes (Lee et al. 2018). Therefore, how network structures affect performance ranks first with the most publications among SNA research in the AEC domain (Zheng et al. 2016). It has been suggested that network metrics such as density, triadic closure, centrality, and tie strength influence sustainability outcomes (Table 2-1).

Table 2-1. Network metrics, definitions, and the use in the context of sustainability

Metric	Definition	The use
Network Density	A measure of whole network and calculated by dividing the number of existing ties by the number of all possible ties (Hanneman and Riddle 2005).	Denser networks might enhance sustainability outcomes, as there is more information exchange (Henry and Vollan 2014). However, sparse networks can improve absorptive capacity and information diversity (Schröpfer et al. 2017).
Triadic Closure	If A-B and A-C nodes in a network have a relationship, B-C will also likely have at least a weak tie (Granovetter 1973).	Triadic closure in networks strengthens trust and therefore has the potential to improve collective action and sustainability outcomes (Henry and Vollan 2014).
Degree Centrality	Degree of a node is the number of other nodes linked to it (Freeman 1978).	The actors with a higher degree can control the information flow in the networks and help spread innovations (Henry and Vollan 2014).
Betweenness Centrality	The measure of whether a person is on the shortest paths between two normally disconnected individuals and linking them (Freeman 1978).	Opportunity to access many unique information and opportunities that other actors do not know can be advantageous in creating sustainability (Bodin et al. 2006; Muñoz-Erickson and Cutts 2016).
Strength of a Tie	The strength of a tie is the "combination of the amount of time, the emotional intensity, the intimacy and the reciprocal services" in a network between nodes (Granovetter 1973).	Weak ties become important when they connect people from different social circles, promote the flow of novel information, and create bridges among clusters that are otherwise disconnected (Granovetter 1973).

To elaborate, higher network cohesion, which can be measured through network density and existence of triadic closures, has positive effects on expertise flows and cooperative behaviors (Frey 2018; Reagans and McEvily 2003). Higher densities might be preferable if the ties between nodes reflect positive emotions, otherwise lower densities may be more suitable better for sustainability outcomes, especially in high-risk environments (Henry and Vollan 2014). In the context of sustainable AEC projects, lower-density networks with strong ties might support tacit knowledge transfers better (Schröpfer et al. 2017). Although triadic closure enhances trust and cooperative behaviors (Reagans and McEvily 2003), it might bring redundancy and a lack of expertise diversity which might inhibit the ability to solve sustainability problems (Henry and Vollan 2014). Therefore, weak ties might become important as the source of necessary and novel information needed in the system (Granovetter 1973). Network centralization and power distribution have also an impact on the sustainability knowledge flows (Muñoz-Erickson and Cutts 2016). In networks, central nodes engage in knowledge-sharing activities more and can control the expertise flows (Baek and Bae 2019). While degree centrality gives an individual the ability to control the knowledge transfers, betweenness centrality enables accessing and synthesizing novel information from different network segments (Muñoz-Erickson and Cutts 2016). If a small number of actors are highly central, they can negatively control the knowledge transfers but this attitude might also help achieve the diffusion of innovations needed faster for sustainability results (Henry and Vollan 2014).

The impact of structural properties on sustainability outcomes depends on network dynamics, such as trust or values (Chinowsky et al. 2008), network context and team structure (Cross et al. 2002), resources flowing in the network, and priorities (Henry and Vollan 2014). Therefore, examining the way nodes are placed and interconnected in a network and understanding the topology of interactions are also important for better sustainability outcomes (Albert and Barabási 2002). Tie content and acquiring diverse knowledge by establishing connections with distinct groups have a positive impact on creative outcomes (Sosa 2011). Additionally, the prevalence of boundary-spanning ties (i.e., network range) that cross organizational, hierarchical, and social boundaries might facilitate novel knowledge transfer and improve performance (Iorio et al. 2012; Reagans and McEvily 2003).

A considerable amount of literature has been published on network metrics but there is not a consensus on what a desirable network looks like, especially for sustainable AEC project projects. There is a need for holistic evaluations and understanding of complex, multi-level AEC project networks utilizing longitudinal and in-depth reviews of network topology in the light of performance parameters.

2.4 Methods

2.4.1 Case Study

To achieve the study aims, we collaborated with an institutional owner organization and were involved in the delivery of a major, institutional renovation and expansion project. According to the institution's construction guidelines, all new construction and major renovation projects are to be Leadership in Energy and Environmental Design certifiable. Upon our request, the owner, and other main organizations (i.e., general contractor and designer) provided data throughout the project delivery for two years. The project had a budget of $20 million and was delivered via Construction Management at Risk. The project team information exchange network included more than 1000 individuals with various levels of backgrounds and expertise, representing owner, designer, and general contractor roles, from 20 different organizations during the design (i.e., schematic design (SD), design development (DD) and construction documents (CD)) and construction phases. We longitudinally collected archival (i.e., meeting minutes and project documents shared on web-based platforms), e-mail exchange and observational data.

2.4.2 Procedure

Archival data constituted of meeting minutes and other documents (e.g., requests for information [RFIs], submittals, and budget sheets) stored on online project management tools and aided the determination of progress loops and performance. Using archival data, we, first, determined the project's progress loops to create a frame for data analyses, as different progress loops correspond to different network structures (Garcia et al. 2014; Marks et al. 2001). The start and end dates of the main episodes (i.e., SD, DD, CD and Construction) were indicated in the meeting minutes. We further broke down the main episodes into monthly time intervals based on the project progress (i.e., cost growth, major milestones, and scope revisions) to thoroughly examine the evolution of networks. In total, the design phase consisted of seven and the construction phase had 12 intervals which lasted approximately four to eight weeks each (i.e., three in SD, two in DD, two in CD, and 12 in construction). After the construction interval 7, the COVID-19 pandemic started and the project team switched to remote working conditions, which was used as a milestone to start interval 8. Archival data also aided the calculation of EA performance, which was used as a measure of sustainability outcomes. Using archival data, we created a Gantt chart to track EA issues over time and calculated EA performance using the percentage of total project issues resolved out of ongoing ones in each time interval. Over the course of the design phase, the meeting minutes were the source to identify the issues about EA. However, after the construction started, the general contractor incorporated online document-sharing platforms and tracked RFIs and submittals online, which are used as performance metrics in the literature while executing green buildings (Raouf and Al-Ghamdi 2019). Therefore, for the construction phase, the ongoing RFIs and submittals were used as well as the issues on the meeting minutes to calculate the performance for each interval.

E-mail exchange logs constituted the main source of communication data and consisted of e-mail headers (i.e., sender, receiver, time, and subject). According to the literature, using e-mail data is an effective method to visualize and analyze AEC project networks (Dogan et al. 2015; Franz et al. 2018). We created Excel macro tools to filter out the irrelevant data based on the e-mail headers. To improve reliability, we interviewed project participants and verified that e-mail data was representative of their project-specific communication patterns. Using e-mail-exchange data as inputs for SNA, we drew sociograms for each interval for the whole team and EA sub-network members and calculated network metrics using Gephi software. To determine the strength of ties between nodes, we assigned 3, 2, and 1 as weights for daily, weekly, and monthly communication, respectively. To evaluate the network topology, we grouped individuals on the sociograms according to: (1) Main roles in the project (i.e., owner, designer, contractor); (2) Tiers of decision-making and operation, (i.e., tier 1 consist of project leads, tier 2 consists of internal employees working for the main roles, and tier 3 consists of all other individuals from external stakeholders contracted to the main organizations); and (3) Expertise areas such as organizational planning and programming, project planning, project needs and program, management, architectural design, civil engineering, mechanical, electrical and Mechanical, Electrical, Plumbing (MEP) construction (Garcia et al. 2020; Mollaoglu-Korkmaz et al. 2014).

Observational data were collected during the weekly project team meetings. Two coders from the research team attended and recorded the number of "information given" by each individual (Frank and Zhao 2005). To ensure reliability, coders met after the meetings to compare and merge their notes. Second, we calculated the rank Spearman correlation between coders to ensure inter-coder reliability. The average correlation was $r = 0.89$, $p < .01$, showing a very similar trend between the coders. Observational data were used as input for SNA node sizing (i.e., give information during project team meetings). Therefore, the larger a node in the networks, the more active the person was in team meetings.

Network boundary specification is of utmost importance to study sustainability networks. Examining ties between actors working for a specific issue or conducting surveys to ask about network members might be helpful to determine network boundaries (Henry and Vollan 2014). In the context of this study, to determine the boundary of the EA sub-network, we examined: 1)

LEED guidelines and determined the roles and expertise areas to ideally collaborate for optimized EA outcomes (e.g., mechanical engineer, occupants, and commissioning authority); and 2) the archival and e-mail data to identify project issues and interactions related to those credits. Accordingly, 83 individuals were included in the EA sub-team.

In this paper, we focused on the entire project delivery to understand the needs and differences of different phases and how the decisions made during the design phase are executed during construction. We conducted two levels of analysis: the whole project team and sub-team relating to the Energy and Atmosphere (EA) issues of the project. After examining the differences between the whole project network and the EA network, we placed the focus on the EA network. Using correlation, we quantified the strength of the relationships between performance-network metrics and performance-network topology measures.

2.5 Results

Figure 2-1, Figure 2-2, and Figure 2-3 depict sociograms for the whole team and the EA sub-team drawn using Gephi and arranged based on team members' attributes (i.e., role, tier, expertise) (see the Appendix for sociograms for all intervals). The number of nodes ranged between 76 (DD interval 1) and 342 (Construction interval 8) in the whole team and 23 (DD interval 1 and SD interval 1) and 56 (CD interval 1) in the EA sub-team throughout the project delivery.

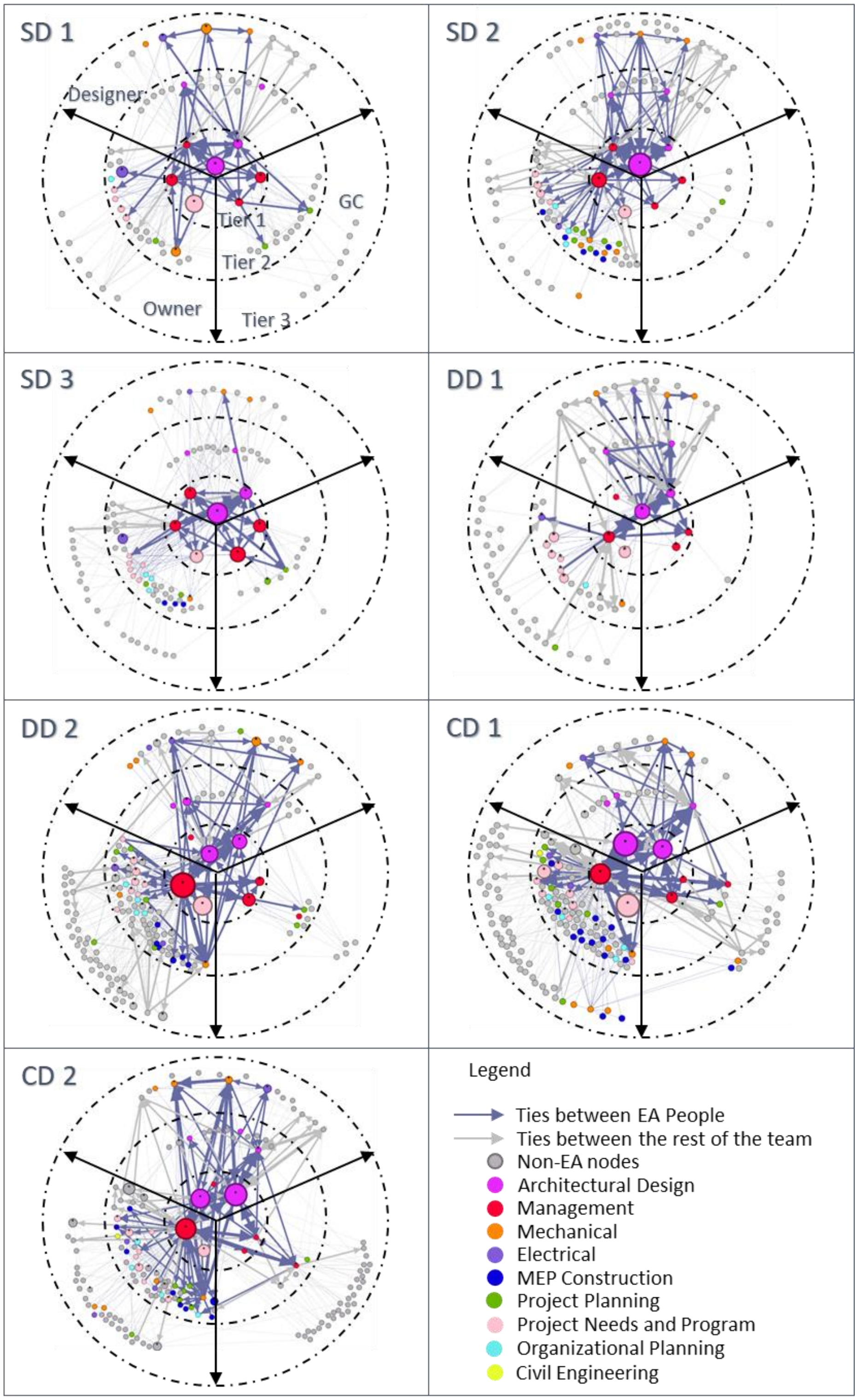

Figure 2-1. Sociograms of project communication network during the design phase displaying network topology. Note: SD= Schematic Design, DD= Design Development, CD= Construction Documents, C= Construction. Different colors for nodes denote different expertise areas.

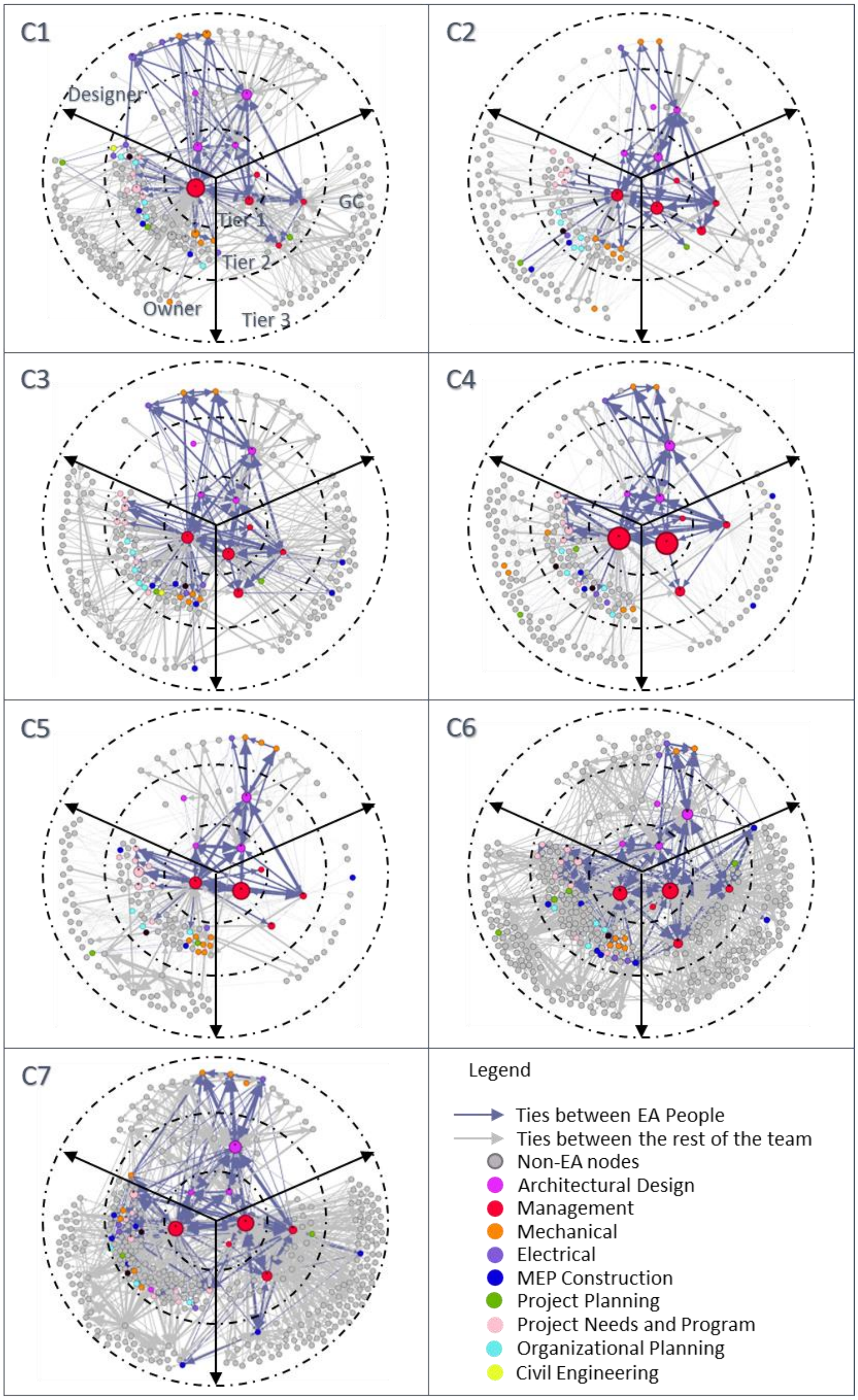

Figure 2-2. Sociograms of project communication network displaying network topology during the construction phase until the start of COVID-19. Note: C= Construction. Different colors for nodes denote different expertise areas.

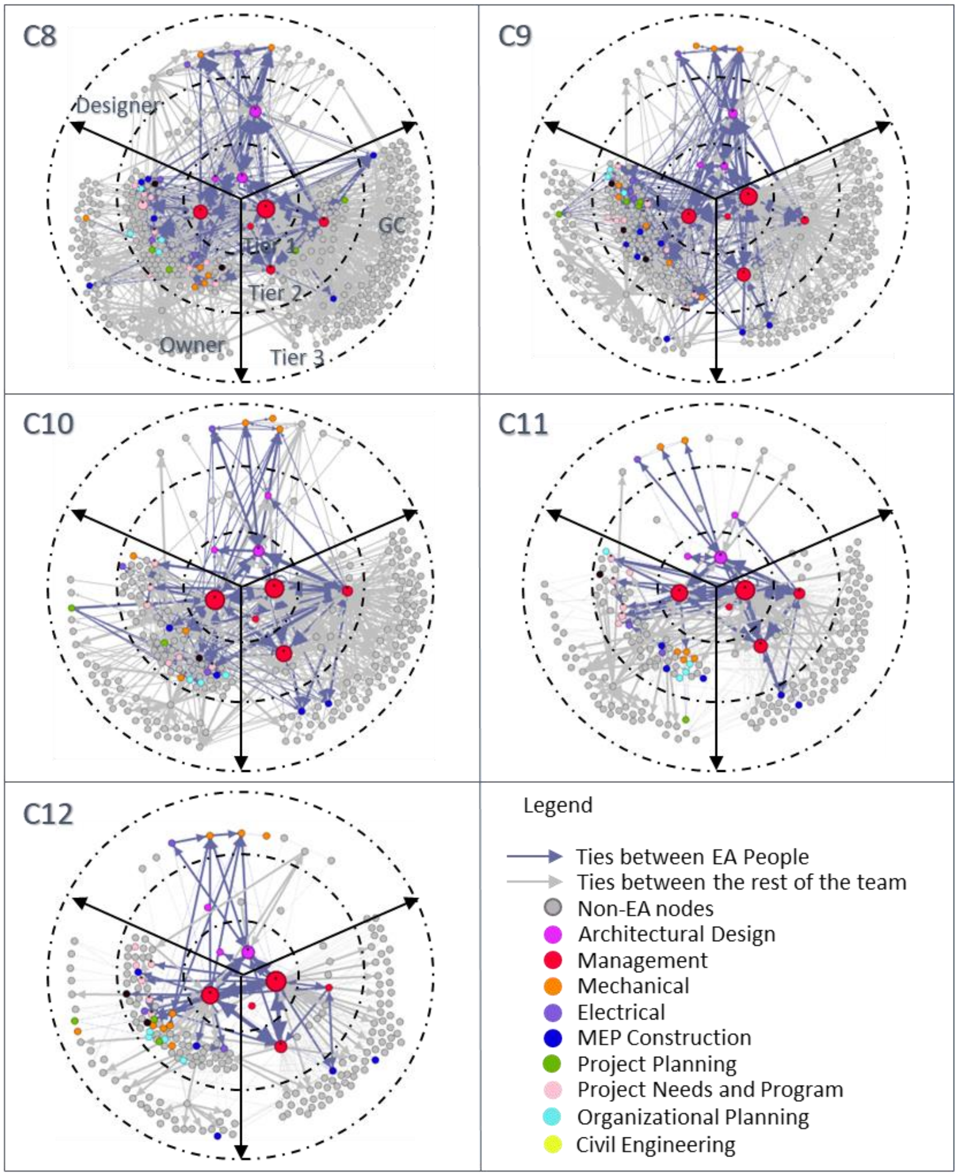

Figure 2-3. Sociograms of project communication network displaying network topology during the construction phase after the start of COVID-19. Note: C= Construction. Different colors for nodes denote different expertise areas.

Two observations were made when we compared the networks. First, the EA sub-team included project team leaders from Tier 1 in different roles. Therefore, they functioned as bridges between different roles and had stronger ties with their EA peers and the rest of the network. Moreover, the sizes of EA nodes are larger in comparison to others, indicating that they have been more active during project team meetings and gave more information. The average of EA sub-team nodes excluding tier 1 leaders was 110 in comparison to others that averaged 30 based on the amount of information given. Second, during the construction phase, the number of nodes in the whole network increased in general contractor role because of the project needs, whereas the EA network mostly remained the same (n= 36 to 50). There were more experts from the owner and designer in the EA networks compared to the general contractor. In construction interval 8 (C8), the COVID-19 pandemic started, and due to slower project progress, longer time intervals were observed (i.e., 7 weeks in comparison to average of 4.7 weeks in prior phases). Moreover, there was an increase in email communication which led to a higher number of nodes (average of 192 per interval versus 342 during C8) and communication ties (average of 611 per interval versus 1394 during C8) in the whole network.

To evaluate the EA networks at the sub-team level, we first calculated the sub-team performance as the percentage of total EA related issues resolved out of ongoing ones in an interval. Table 2-2 exhibits performance of EA team throughout the project delivery ranging between 0%-90.1%, where construction 6 interval has the highest performance (i.e., 90.1%).

Table 2-2. Energy and Atmosphere (EA) sub-team performance based on issue resolution rate

	SD1	SD2	SD3	DD1	DD2	CD1	CD2	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
A	8	10	5	5	13	7	4	2	2	10	28	19	11	12	12	9	9	15	11
B	3	6	3	0	7	4	3	1	1	6	24	16	10	9	9	7	3	8	9
C	**37.5**	**60**	**60**	**0**	**53.8**	**62.5**	**75**	**50**	**50**	**60**	**85.7**	**84.2**	**90.1**	**75**	**75**	**77.7**	**33.3**	**53.3**	**81.8**

Note: A) The number of total issues in each interval B) The number of issues resolved in each interval C) Issue resolution rate calculated as a percentage. SD= Schematic Design, DD= Design Development, CD= Construction Documents, C= Construction.

We then performed SNA at the EA sub-team level. Figure 2-4 shows the network metrics along with the performance values. The network density (i.e., the ratio of existing ties to possible ties, ranging between 0 and 1) remained low throughout the project delivery ranging between

0.063- 0.245, while global clustering coefficients (i.e., the ratio of existing triadic closures to possible triadic closures, ranging between 0 and 1) were ranging between 0.383- 0.716. As the indicators of network cohesion, both network density and clustering coefficient did not show any relationship with the performance (i.e., the correlation coefficients *r*= -0.42, and *r*= -0.23 between performance-density and performance-clustering coefficient). In a similar trend, the correlation coefficient between the average degree and performance was not significant (*r*= -0.26). Only average betweenness centrality had a moderate correlation with the performance for the whole project delivery (*r*= 0.54). In summary, network metrics did not correspond to the changes, disruptions, or the needs of the network within the context of EA project issues.

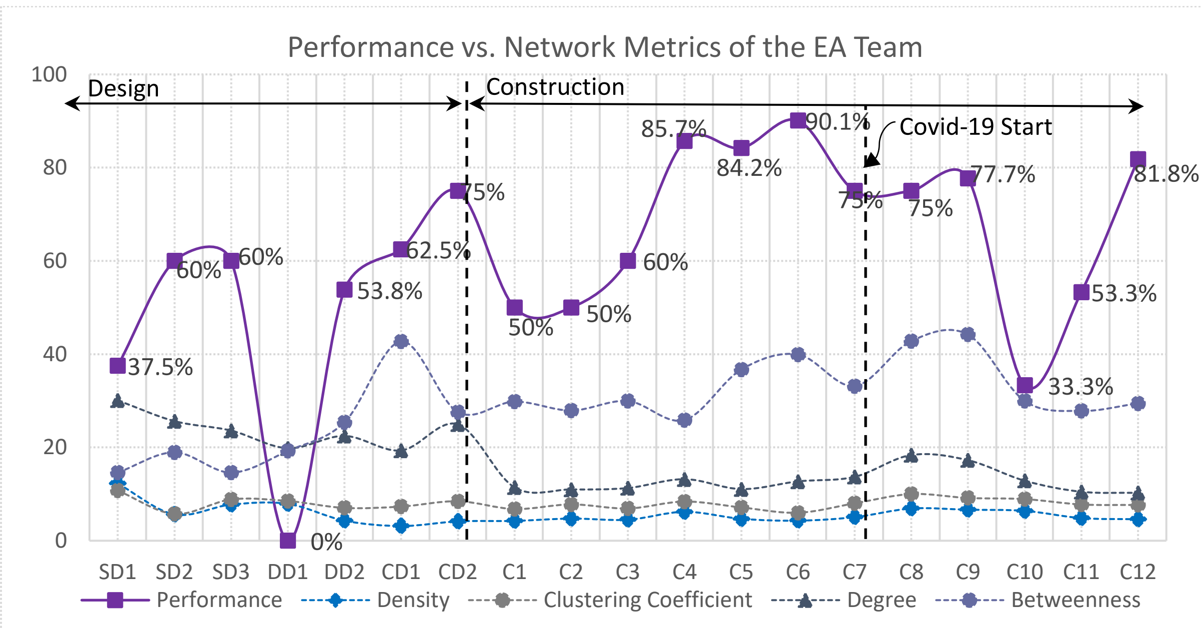

Figure 2-4. EA Sub-team performance vs. network metrics during project delivery. Note: SD= Schematic Design, DD= Design Development, CD= Construction Documents, C= Construction. The values for network metrics were multiplied to better illustrate the relationship on the graph.

After examining the network metrics, we focused on the network topology. Figure 2-5 shows the relationship between performance, total network exposure, and boundary spanning ties. First, we calculated the total expertise exposure for each interval as the summation of all interactions considering the strength of the ties (i.e., 3, 2, and 1 for daily, weekly, and monthly communication). We observed that there is a similar trend between total exposure and performance for the design phase (*r*= 0.91) and first half of the construction until the end of the interval 7 (*r*= 0.85). However, due to the drastic increase in e-mail communication after the COVID-19 started, the correlation coefficient between the total exposure and performance dropped to insignificant levels (*r*= 0.41). The results showed that even though the network density was low, increased expertise exposure and performance were positively correlated until the end of C7. Similarly, we observed a similar trend between the number of boundary-spanning ties and performance. We observed that there is a link between the performance and the number of EA experts in the networks during the design phase (r= 0.74) and the construction phase (r= 0.60) with no difference between pre-and post-COVID-19 phases indicating the importance of expertise diversity especially for the design phase.

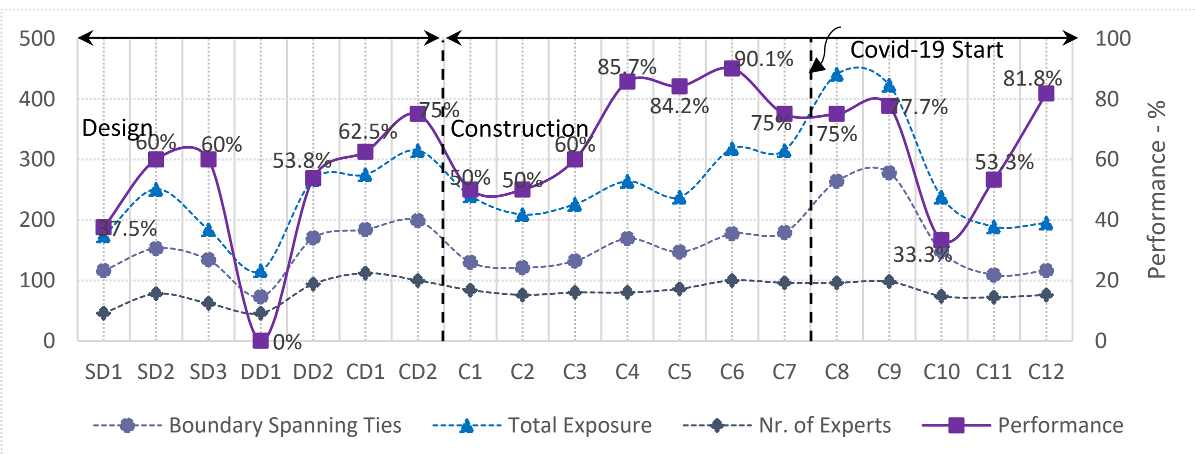

Figure 2-5. Performance vs. Boundary spanning ties & Total exposure & Number of experts in the sociograms. Note: SD= Schematic Design, DD= Design Development, CD= Construction Documents, C= Construction. The values for Nr. of experts were multiplied to better illustrate the relationship on the graph.

To enable data triangulation, we analyzed the observational data after examining collaboration networks based on the e-mail communication data. Figure 2-6 shows the relationship between the number of information given by the EA experts from different expertise areas during the weekly team meetings along with performance values.

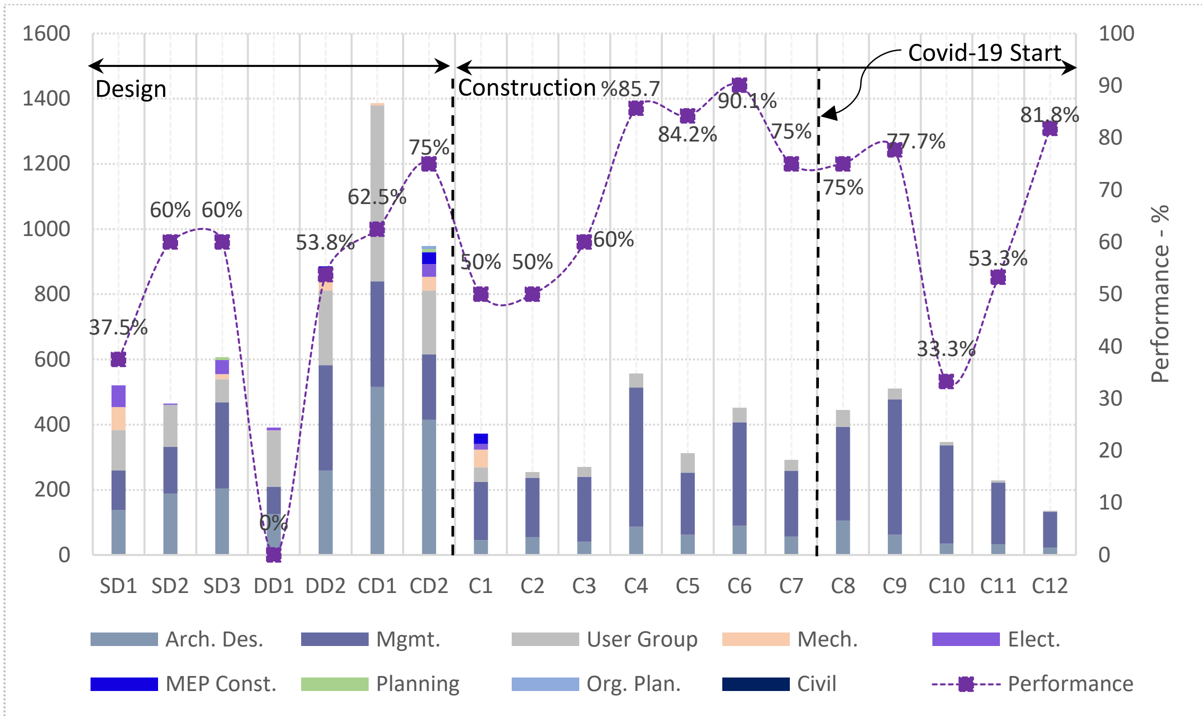

Figure 2-6. Total information given during team meetings by expertise area vs. E-A sub-team performance

There is a moderate relationship between the total number of information given in an interval with the performance for the design (r= 0.57) and the pre-COVID construction phase (r= 0.58). Architectural design, management, and user group expertise areas were consistently represented in the meetings. Team members with mechanical, electrical, MEP construction, project planning, organizational planning and civil engineering expertise areas attended the meetings based on the needs of the project (as detected in archival documents). For example, mechanical designers attended the weekly team meetings along with the user group, management team and architectural design team to finalize the selection of mechanical systems considering architectural layout, budget constraints and constructability.

During CD 1 interval, there was an increase in the amount of information shared in meetings, which might have yielded the highest performance in design phase during CD interval 2 with a lag. Moreover, during CD2, where the performance was highest, all expertise areas were represented in team meetings. Similarly, during DD interval 1, where the performance was lowest, the amount of information given was also the lowest with the lack of expertise representation in team meetings. During the construction phase, expertise diversity remained low with the attendance of management, architectural design, and user group experts (except C1) but it did not impact the issue resolution rate. Project close-out was against the trends with high issue resolution rate despite the low communication.

Contrary to expectations, this research did not observe any trends between the network metrics and performance except for betweenness centrality at moderate level (r= 0.54). Especially network density and clustering coefficient did not positively impact performance. However, increased exposure and expertise flows through existing ties are positively related to performance as well as the increased network range via boundary spanning ties. Disruptions, such as COVID-19, impacted the way the network functioned but the tendency of using e-mail communication more did not increase the performance to the same extent. The results also indicate that design and construction phases showed different needs pertaining to the number of experts in the networks and expertise diversity during the team meetings. During the design phase, the highest performance occurred when team members from different roles, tiers, and expertise areas exchanged information via e-mail and during the team meetings.

2.6 Discussion

Sustainable AEC project delivery is complex with the involvement of diverse disciplines and high-tech components and the performance of a project hinges on successful expertise integration and collaboration. The outcomes of this research provide theoretical and practical implications that facilitate expertise flows to achieve optimal sustainability outcomes.

First, the EA network was at the center of the project network with the involvement of project leads from tier 1. Moreover, more experts from the owner and designer were involved in the EA networks compared to the general contractor. The findings support that the owner plays an important role in the EA collaboration during design (by communicating the needs of the user group with the designer group to determine the scope of EA systems) and construction (for the commissioning of the EA systems) (Castro-Lacouture et al. 2008).

Second, in contrast to earlier findings, no evidence of relationship between network metrics and performance was detected. There was almost an inverse relationship between the EA performance and network density, clustering coefficient, and average degree. Findings in the present study are consistent with the findings of Schröpfer et al. (2017) and support the idea that instead of higher density networks where everyone is connected to each other, sustainability expertise flows through the existing strong ties. Similarly, we could not identify any relationship between the increasing clustering coefficients and the performance. Even though triadic closure might improve trust and collaboration between nodes, it might also inhibit nodes to access novel information and can have an adverse effect on sustainability outcomes (Henry and Vollan 2014). Only average betweenness centrality had a moderate correlation with the performance for the whole project delivery, proving that brokers with high betweenness centrality gain and synthesize specific knowledge and might help facilitate collective action (Burt 2004). The results indicate the importance of brokers, especially during times of disruption like COVID-19, as they also know when and how to engage with groups or individuals (Bodin et al. 2006; Burt 2004).

Third, increased exposure and network range via boundary spanning ties had a positive relationship with the performance. Figure 2-7 shows an example of two networks with the same exposure value (i.e., 8) and different densities (i.e., 1 and 0.66). Results suggest that the second network might be more favorable for the sustainability outcomes, especially when the people from diverse expertise areas and across boundaries are connected (Marco et al. 2010). Even though increased exposure and boundary spanning ties had a positive relationship with the performance, there was a point of diminishing results after COVID-19 started. The results demonstrate that excessive expertise flows might increase the inefficiency and reduce the absorptive capacity (Schröpfer et al. 2017).

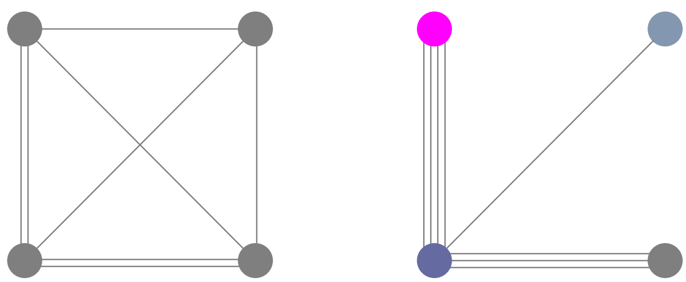

Figure 2-7. Sample communication networks of four individuals with the same exposure and different density values. Note: Color denotes different expertise areas. The number of links denotes the frequency of communication between two individuals.

The results also indicate that design and construction phases showed different needs pertaining to the number of experts in the networks and expertise diversity during team meetings. During the design phase, where most crucial decisions with the highest impact on construction execution and building outcomes occur, the highest performance occurred when team members from different roles, tiers, and expertise areas exchanged information via email and during team meetings (AIA 2007).

The study findings above have important implications for interdisciplinary complex project teams and the project management discipline. First, we presented network metrics to evaluate expertise flows. We posit that focusing solely on network metrics is not enough for advanced sustainability outcomes. The structural properties of the networks might not necessarily reflect or fulfill the needs of the real networks (Boccaletti et al. 2006). Evaluating the topology of complex networks longitudinally would lead to a better understanding of collaboration and interaction patterns by focusing both its dynamical and mechanical behaviors (Boccaletti et al. 2006; Chinowsky et al. 2008). Briefly, evaluation of network topology by looking at the forces formed it, the way nodes are interconnected, positioned, and expertise diversity improves the sustainability outcomes. Network topology with boundary spanners and diverse expertise areas enhances the actions and abilities of the individuals by stimulating expertise flows. The finding recommends two practical strategies: (1) Project management should determine the boundaries of the EA networks to determine the parties that ideally should collaborate and enable expertise diversity, (2) project management should enable targeted involvement of the experts to avoid information overload by creating communication protocols.

2.7 Conclusion

The unique nature of sustainable buildings requires additional considerations beyond conventional construction projects in their delivery and a high level of expertise integration is needed to optimize systems and performance. However, there is a knowledge gap regarding what network characteristics are favorable for improved sustainability outcomes in AEC projects. This study contributes to the body of knowledge by holistically examining the evolution of an AEC project network and associated characteristics that allow experts to exchange knowledge to optimize sustainability outcomes.

Results suggest that focusing merely on network metrics, such as density, degree, and clustering coefficient, does not correspond to network needs. Evaluation of network topology is important to understand expertise flows needed for optimized sustainability outcomes. Increased exposure in low density networks has a positive impact on performance indicating that key connections in networks, such as boundary spanning ties, are more valuable than others and should be targeted to improve efficiency. It was also observed that design and construction phases have different integration patterns and changes in expertise diversity has a direct impact on performance during the design, where the decisions are made. Therefore, the findings suggest that project management team should ensure to define the project needs, select the team members accordingly and guide information sharing behaviors to avoid information overload.

The main limitation of this study is that the results were drawn from a single case study, which might limit the generalizability of the findings. Future research should investigate the metrics studied herein in project teams with different characteristics. Second, this study does not take into account the issue complexity, or the number of issues assigned to a party in an interval while calculating the performance based on the issue resolution rate. Future research can elaborate performance calculations by considering issue complexity or the number of issues for each party. Nonetheless, the study provides SNA methods to improve sustainability that can be applied to networks in any complex project team.

2.8 Acknowledgements

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3 INTERACTIONS OF CROSS-LEVEL KNOWLEDGE TRANSFER IN PROJECT NETWORKS: SOCIAL INFLUENCE ANALYSIS

3.1 Abstract

Complex project teams gather individuals with diverse and complementary skills who work together to achieve a shared goal but often fail to collaborate efficiently. Therefore, there is a need to find ways of achieving improved collaboration to fulfill project requirements. Cross-level knowledge transfer occurs between individuals, across groups, and across the entire team within project networks; enhances collaboration; and triggers behavioral changes in team members due to social influence mechanisms. However, little is known about how project-level knowledge transfer among all members influences the group-level transfer knowledge in a sub-team. This study establishes a social influence model to understand cross-level knowledge transfer in project networks with a focus on energy-efficiency sub-team. To achieve the study goals, the researchers longitudinally collected archival and e-mail exchange data during the delivery of a complex construction project and analyzed the knowledge-transfer networks using social network analysis and the social influence model. Results confirmed that diverse project-level knowledge transfer impacts group-level knowledge transfer within project collaboration. The findings elucidate the knowledge transfer process along with project team member communications and suggest that: (1) Knowledge-transfer of team members is dynamic and influenced by the information acquired from their connections in the team; (2) Exposure to diverse information within a project team promote knowledge flows at the group-level; (3) Team members with high eigenvector centrality are those that highly influence others in a project and might help increase centrality for the whole team by spreading their attitudes; and (4) Opinion leaders are difficult to be influenced and may inhibit the team's innovative capacity.

3.2 Introduction

Architectural, Engineering, and Construction projects are complex with the involvement of many stakeholders, tiers of organizational assignments, and sub-teams performing under time, cost, and other pressures to deliver a unique product (Buvik and Rolfsen 2015). A diverse group of individuals with different and complementary expertise, motivations, and backgrounds forms the project teams and are expected to collaborate for performance optimization during project delivery (Kratzer et al. 2010; Mollaoglu-Korkmaz et al. 2013). Based on the project needs, project teams are divided into different sub-teams (i.e., groups), which are nested in a project team and working on different tasks, while collaborating with other project team members towards the project goals (Garciacortes 2017). For example, when an electrical contractor is roughing-in, they coordinate with the design team to execute the project properly; while the design team cooperates with consultants and vendors to determine the details of the design. Due to this complex and cross-level structure of knowledge transfers needed across groups, project teams often fail to meet expectations. To address the challenges of complexity, project teams need to practice integrative collaboration by engaging in cross-level, cross-domain, and cross-organization knowledge transfers (Garcia et al. 2021).

In the organizational sciences literature, knowledge transfer refers to the behavior of sending and receiving knowledge, disseminating ideas, and providing and getting inputs acquired in one situation to another for problem-solving (Singley and Anderson 1989; Szulanski 1996). Knowledge transfer involves continuing social interactions among project members, triggers certain behavior patterns (Nonaka 1994), and results in social contagion. Contagion theories are based on a disease metaphor, where interaction leads to contamination, in other words social influence (Monge et al. 2003). The social influence theory explains the social mechanisms of how individuals alter their attitudes, emotions, beliefs, and behaviors when exposed to knowledge or emotions during social interactions (Kaufer and Carley 2012; Kelman 1953). Since the organizational culture is formed by employees' adoption to changes and their environment (Schein 2010), behavioral changes happening as a result of the influence processes contribute to organizational culture (Frank and Fahrbach 1999).

The project management literature addresses different aspects of knowledge transfer such as factors impacting successful knowledge transfer in inter-organizational teams (Bakker et al. 2011; Garcia and Mollaoglu 2020), transferring organizational knowledge across projects (Wei and Miraglia 2017), knowledge transformation across organizational and specialization boundaries (Alin et al. 2011), and motivations boosting knowledge transfers (Chinowsky et al. 2008). However, it is not clear how social interactions at the project level influence the way individuals transfer knowledge at the group level within projects and vice-versa. Without this information, it would be challenging for project managers to understand whether cross-level, multidisciplinary knowledge transfer or domain-specific knowledge transfer should be facilitated for higher project performance.

To address this problem, the objective of this study is to identify the social influence on knowledge transfer across project and group-levels of project collaboration. Specifically, the study aims to elucidate how project-level knowledge transfer, including all team members from all groups, influences group-level knowledge transfer in complex project collaborations. We define social influence as attitude and behavioral changes through exposure to information and social interactions (Frank et al. 2018; Marsden and Friedkin 1993). Methodologically, we use social network analysis (SNA) technique to analyze network structures and examine the structural properties relating to social interactions including centrality or core-periphery membership

(Borgatti and Everett 2000; Hanneman and Riddle 2005). We then establish social influence models to gain quantitative evidence if there is a relationship between project-level and the group-level knowledge transfer.

In this study, we examine the energy-efficiency group and their group-level knowledge transfer to test the research question. Sustainability becomes a core value for organizations and construction projects to address energy crisis and climate change (Korkmaz et al. 2010). Buildings remarkably deplete 55% of global electricity and 40% of global resources (United Nations Environment Programme 2020) and under the current scenario, the upward trend in global energy consumption and energy-related carbon dioxide emissions will go on through 2050 (U.S. Energy Information Administration (EIA) 2021). Due to the increasing depletion of energy and resources, construction projects are required to be energy efficient. However, the inherent nature of sustainable buildings presents additional complexity to projects, requiring group members with diverse skillsets to further collaborate and coordinate with people across levels for acquiring collective knowledge, and innovative solutions (Korkmaz et al. 2010; Riley et al. 2004).

3.3 Literature Review

3.3.1 Knowledge Transfer in Project Networks

Project teams are transient organisms consisting of organizations and individuals with diverse expertise areas (Garcia et al. 2020). Team members combine their knowledge and strengths by interacting in systematic ways to deliver a project within performance criteria measured in cost, time, quality, safety, and sustainability (Chinowsky et al. 2008; Kereri and Harper 2019). As new knowledge and solutions are generated as a result of such social interactions (Nonaka 1994), the social network approach has emerged as a robust tool for studying knowledge transfer in project teams (Chinowsky et al. 2008; Zheng et al. 2016).

SNA is a method of assessment and calculation of relational and social structures (Butts 2008). It is a robust approach to visualize and mathematically assess the interaction patterns of the project team members (Duva et al. 2020; Zhao et al. 2021). The smallest network is formed by two individuals (will be referred to as nodes hereafter) and one relationship (will be referred to as ties hereafter) linking them, called dyad. Bigger networks can be studied through sociograms, in which relationship schemes of individuals in a network are visualized. Network structures can be systematically calculated by using network properties such as degree, distance, or centrality (Hanneman and Riddle 2005). Network properties are important to characterize the network topology, and understand "how and why" things happen in a network (Golbeck 2013). Moreover, in networks, structural properties were found to be appropriate in measuring influence (Brass 1984) as network properties of surrounding nodes affect the attitudinal and behavioral responses of the actors (Pauget and Wald 2013). Especially, influence in a network has been linked to the centrality of an actor in a network, as centrality reflects an individual's power, status, or importance (Brass 1984) and the importance of nodes in a network spread out to the nodes that they are connected to (Golbeck 2013).

In a network, the nodes with the highest centrality can control knowledge flows and affect the diffusion of information. Central nodes in a network participate in knowledge sharing activities more actively (Baek and Bae 2019). For example, outdegree centrality is the amount of ties that a node builds with other actors in a network and shows the level of engagement (Freeman 1978). In other words, it can be used to determine the individuals directly influencing others in a social network (Das et al. 2018). Similarly, eigenvector centrality is a measure of determining influential individuals in a network and calculates the centrality of a node based on the links from important nodes and their centralities (Bonacich 1972). Therefore, eigenvector centrality measures strategic and long term direct and indirect influence, whereas outdegree centrality is a measure of immediate influence (Borgatti 2005). Therefore, eigenvector centrality is an ideal measure to use as an indicator for social influence processes and changes in knowledge transfer. Moreover, the relationship between eigenvector centrality and knowledge transfer behaviors will be discussed in the methodology section.

3.3.2 Social Influence in Project Collaboration

The social influence theory explains how individuals change their beliefs, attitudes, or behaviors to conform to the norms of their social environment (Li et al. 2018). Conformity can occur in normative form (i.e., when a person changes behavior with the expectations of being liked) or informational form (i.e., when a person lacks the knowledge and acquires it from a group) (Deutsch and Gerard (1955). In this paper, we define social influence as attitude and behavioral changes through exposure to information, as dissemination of information is followed by influence flow (Li et al. 2018).

In project collaboration, individuals begin interactions with certain opinions, and as the project proceeds, they alter their beliefs, attitudes, or actions as a result of their interactions with others. Influence starts at the dyad level when two individuals attempt to solve a problem by collaborating and creating new knowledge (Poleacovschi et al. 2017). Basic influence processes at the dyad level yield complex interaction and behavior patterns (Frank and Fahrbach 1999). By promoting necessary interactions, influence and diffusion of desired practices can be enabled for better project outcomes (Kadushin 2012). Therefore, it is important to examine knowledge transfer at different levels to get an insight into how organizations and project networks function (Foss et al. 2010; Javernick-Will 2012).

Froehlich and Carbonell (2022) discuss social influences in the context of team learning at three levels (i.e., macro-level (organizational network), meso-level (team), and micro-level (team members)) to achieve project goals and proposes using SNA and relational data to identify patterns, structures, and positions. The study also presents that team learning at different levels is interrelated and influences each other. Peters et al. (2017) examines social influence via two construction projects to develop an understanding of how diffusion of knowledge and network learning occur through contagion mechanisms in inter-organizational project networks. The study presents that face-to-face negotiation, such as friendship ties; socialization, such as humor and informal communication; and utilization of artifacts trigger attitude change through contagion.

Even though it has a great impact on project performance, few studies have examined the way individuals establish their relationships and influence each other in terms of knowledge transfer in complex project teams (Chang et al. 2013; Kereri and Harper 2019). It is necessary to establish a social influence model to quantitatively elucidate the evolution of project collaboration networks and obtain insights into its impact on knowledge transfer.

3.3.3 Network Boundaries and Social Influence

While evaluating social influence in networks, organizational and individual characteristics should also be taken into the account (Frank et al. 2018). Roles impact the influence processes because certain behavior patterns and expectations are attributed to different roles (Marsden and Friedkin 1993). Influence is also contingent on individuals' attitudes (Penuel et al. 2013). Overlooking individual characteristics might lead to uncoordinated practices and impair an organization's effectiveness in implementing innovations (Frank et al. 2018).

Project collaboration networks might not always follow the organizational assignments and there might be a misalignment between them as shown in Figure 3-1 (Hossain 2009; Zhao et al.

2021). Therefore, this study groups individuals based on their comparative level of activity in collaboration networks (i.e., core/periphery status) (Borgatti and Everett 2000) as well as their organizational assignments in the project network (Mollaoglu-Korkmaz et al. 2014). In core-periphery structures, the core consists of a small number of members, who interact frequently, whereas the periphery indicates the members who are connected to the core sparsely (Borgatti and Everett 2000). Based on contractual relations and decision-making power, there are tiers and roles in a project organization network (Mollaoglu-Korkmaz et al. 2014): Tier 1 includes project managers; Tier 2 represents individuals from home organizations of Tier 1 members; and Tier 3 represents all other individuals including subcontractors, vendors, and consultants. Roles (i.e., designer, owner, and GC in the context of this study) and tiers figure below is based on organizational assignments, but anyone can be in the core team in a core/periphery collaboration network at any given time during project delivery despite the formal organizational role, tier, and expertise area.

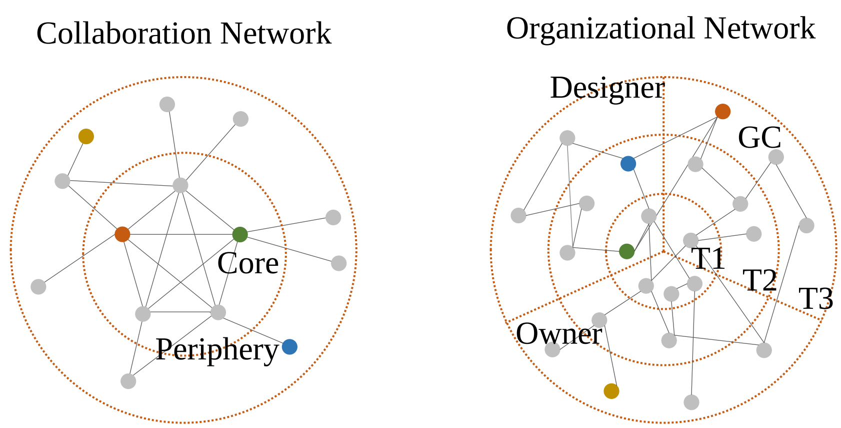

Figure 3-1. Project networks according to organizational assignments and communication behaviors. note: while organizational network is based on assigned roles, anyone can be in the core regardless of role, tier, or expertise area. Note: Different colors indicate different expertise areas. T1= Tier 1, T2= Tier 2, T3= Tier 3.

Determining core and Tier 1 members of the networks is important as those people might be opinion leaders and have different influence patterns in comparison to the rest of the team.

Opinion leaders tend to be well-connected to their network and good at influencing others (Kadushin 2012). However, they cannot deviate from community norms not to lose their positions in the network. In other words, they might not get influenced as much as others do (Valente 2010).

3.4 Methodology

3.4.1 Data

The data included archival data (i.e., documents shared on online project management software and meeting minutes) and e-mail exchange logs. The data were collected in collaboration with the project owner, contractor, and designer. The archival data aided the creation of a timeline for data analyses and determining the energy-efficiency group members. Email exchange logs, consisted of email headers (i.e., sender, receiver, time and subject line), were the main source to generate knowledge transfer networks and examine influence occurring, as influence does not merely occur as a result of face-to-face interaction and the only precondition for influence is exposure to information (Marsden and Friedkin 1993). Extraction of email data is an arduous work but it eliminates self-reporting bias as it leaves a record, allows working on a big data set, and facilitates new insights (Kadushin 2012). Moreover, email exchange data are reliable in understanding actual communication flows (Quintane and Kleinbaum 2011). To eliminate unrelated e-mails, we discarded the non-project-specific emails using the email headers. In-person interviews with project leads verified that email data and communication patterns illustrated in the networks reflect overall project-specific team interactions, as team members were required to send follow-up emails for documentation purposes when they used a different media for communication (e.g., face-to-face or phone calls).

We longitudinally collected data from a Leadership in Energy and Environmental Design (LEED) certifiable, expansion and renovation project that ran between 2018 and 2021. The project was budgeted at $20M. Data collection phase spanned over the design and construction phases throughout the project delivery (see Figure 3-2). The design phase of construction projects is usually divided into schematic design, design development and construction documents episodes.

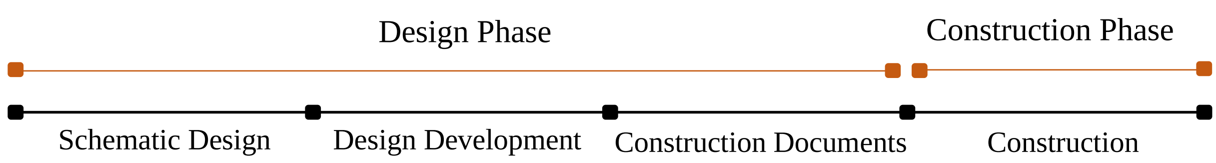

Figure 3-2. Timeline of project delivery

3.4.2 Procedure

Figure 3-3 summarizes the data collection and preparation procedure. The first step was using the archival data to determine the project episodes (i.e., schematic design, design development, construction documents, and construction). Using project episodes as the key time points of reference, the study evaluated social influence processes longitudinally, unlike most social influence studies using cross-sectional data (Marsden and Friedkin 1993).

The second step was to generate sociograms and conduct project-level SNA for each episode using e-mail logs. We determined the strength of the ties between nodes based on e-mail exchange frequency and assigned 3, 2, and 1 as weights for daily, weekly, and monthly communication, respectively. The archival data (e.g., team rosters, and weekly/ biweekly project team meeting minutes) were then used to determine node characteristics (i.e., expertise, roles, and tiers) in the whole network. We also ran a core-periphery analysis to identify the core members of the networks by using UciNet.

The third step was to identify energy-efficiency group members in the project team using the archival data and conduct group-level SNA for each episode. Expertise areas and roles that should be collaborating in construction project teams for improved energy-efficiency outcomes include: owner, commissioning authority, building manager, lighting designer, contractor, occupants, and mechanical engineer (USGBC 2020). Additionally, we scanned the e-mail logs to determine the individuals working on the project's energy-efficiency issues such as the selection and commissioning of building energy systems to enable data triangulation. After determining the energy-efficiency group members, we drew group-level sociograms for each episode.

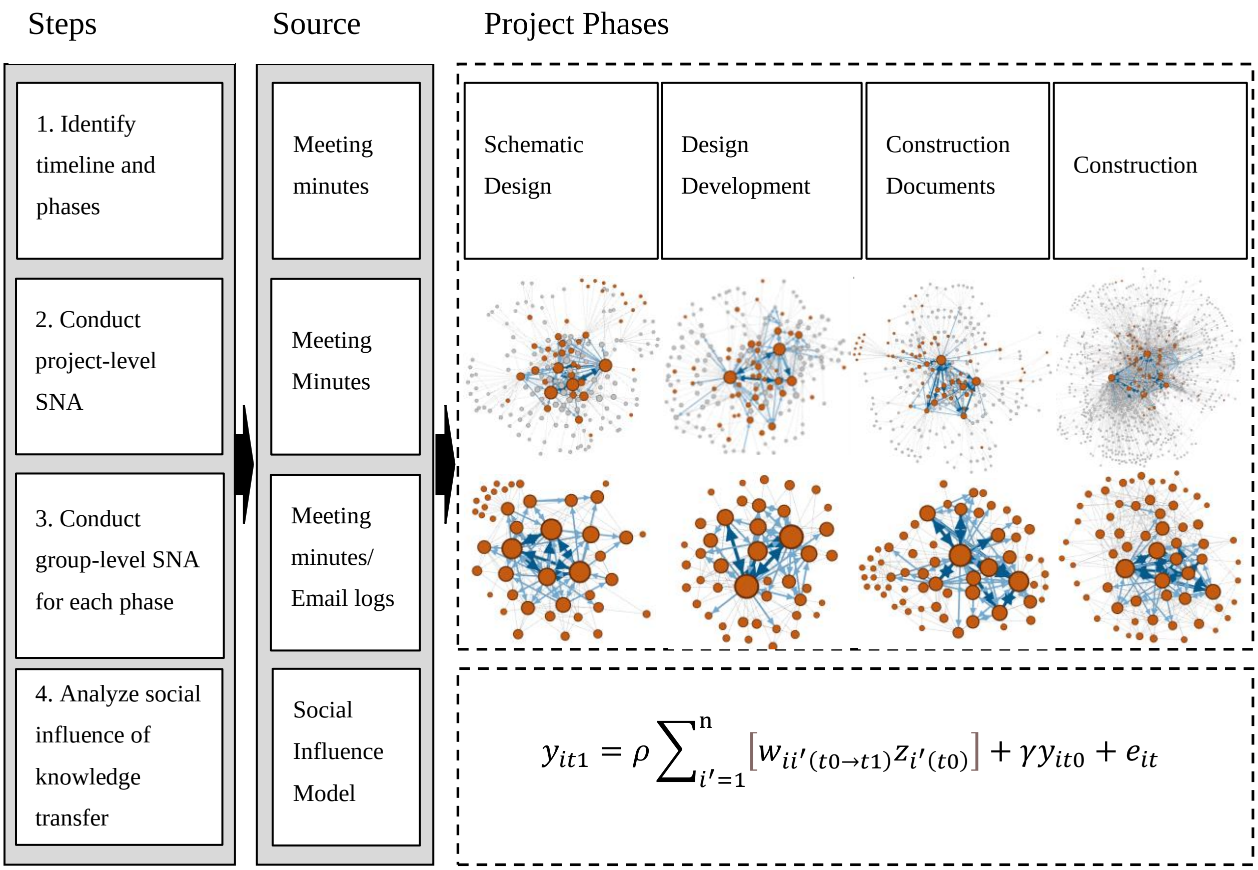

Figure 3-3. Summary of data collection and preparation. Note: Orange color denotes the energy efficiency group. Node size denotes eigenvector centrality.

The fourth step was evaluating the influence by using the network analysis results from steps two and three. As described above, we conducted SNA for each episode at two levels by using Gephi: (1) The project level which involves all experts working in the project team; and (2) the group level which involves the experts collaborating towards energy efficiency goals. After drawing networks, we obtained the eigenvector centrality from Gephi as a measure of knowledge transfer for each individual and calculated the social influence as explained in the section below. As discussed in the literature review, eigenvector centrality was selected to calculate influence, based on the theory and previous work. Even though outdegree centrality was promising in capturing influence (Duva et al. 2022), it accounts for the connections from a single person and shows immediate influence (Borgatti 2005). Therefore, it is a measure of an egocentric network and gives less importance to the complete network. However, eigenvector centrality assigns relative scores to individuals based on the pattern of ties across the whole network (Bonacich 1972). Therefore, it is an ideal measure of determining influential individuals and for using social influence processes (Borgatti 2005). Additionally, we conducted analyses to see if the eigenvector centrality can be a proxy for knowledge transfer behavior as represented by knowledge sharing behaviors in face-to-face meetings. To calculate information sharing behaviors, two members of our team observed the weekly project team meetings and systematically recorded the number of times “information was given” by each individual in the meetings for each episode (the average correlation coefficient for intercoder reliability was r= 0.89). The average correlation coefficient between eigenvector centrality and information sharing behaviors of individuals in the meetings was r=0.75 for all episodes. As the number of meeting attendees is lower than the number of all project members in the project networks, we used eigenvector centrality to holistically evaluate the influence processes in project teams.

3.4.3 Social Influence Modeling

In organizations, influence occurs as a result of an interaction between two people (Freeman 1984), and the influence process can be analyzed via the social influence model in a social network (Frank and Fahrbach 1999). We used the social influence model below adopted from Frank and Fahrbach (1999) and Marsden and Friedkin (1993), in which the influence is a function of exposure of *i* to the attributes of *j* through interaction:

$$y_{it1} = \rho \sum_{j=1}^{n} \left[w_{ij(t0 \to t1)} z_{j(t0)} \right] + \gamma y_{it0} + e_{it}$$

y_{it0}	Group-level eigenvector centrality of the node *i* at time t_0, denoting the original potential knowledge transfer of member *i* within the energy-efficiency group network.
y_{it1}	Group-level eigenvector centrality of the node *i* at time t_1, denoting the subsequent potential knowledge transfer of member *i* within the energy efficiency group network.
$w_{ij(t0 \to t1)}$	Project-level interactions received by *i* from *j* during the period of t_0 - t_1.
z_{jt0}	Project-level eigenvector centrality of the node *j* at time t_0, denoting the original potential knowledge transfer of member *j* in the project network.
$\sum_{j}^{n} w_{ij(t0 \to t1)} z_{j(t0)}$	Project-level exposure, indicating potential influence of project member *j* on group member *i* during the period of t_0 - t_1.
ρ and γ	ρ represents the degree of influence and γ represents the extent to which people repeat prior behaviors.
e_{it}	Error term.

According to the social influence model, the knowledge transfer of an actor *i* at the group level at t_1 (y_{it1}) depends on the exposure that the actor gets from the whole project network and the actor's previous knowledge transfer at t_0 at the group-level (y_{it0}). Exposure is calculated as the summation of interactions with individuals multiplied by the knowledge transfer of those individuals interacted in the project network ($\sum_{j}^{n} w_{ij(t0 \to t1)} z_{j(t0)}$). For example, if person A interacts with B and C who have levels of central of .5 and .9 respectively then person A is exposed to centrality scores summing to 1.4.

We used the social influence model to analyze the social influence of knowledge transfer in three different time points, namely, schematic design-design development (analysis 1), design development- construction documents (analysis 2), and construction documents- construction (analysis 3). For example, for analysis 1, new sustainability knowledge transfer (y_{it1}) was calculated as the eigenvector centrality in the energy-efficiency group network in the design development episode, which was a function of the exposure occurring during the schematic design phase in the project network (t_0-t_1) and the sustainability knowledge transfer at the schematic design episode in the energy-efficiency group network (y_{it0}). As the robustness of these three analyses varied but showed evidence of influence, we also estimated a single influence model by stacking the data from three times points to understand how influence occurred throughout the project delivery.

3.5 Results

Table 3-1 shows the number of nodes in the project-level network and group-level network for each episode. We estimated the analyses for the energy-efficiency group members who were present in two successive episodes. The number of individuals (i.e., observation number) for analysis 1 was 34 and 39, and 48 for the successive analysis, respectively. The exposure calculated for energy-efficiency group members was based on their interactions in the project network as mentioned in the methodology. Tier 1 (representing assigned leads in the project organization) and core member (representing emerged leads in the communication network) numbers in the project network are also identified in the table.

Table 3-1. Numbers of network members. Note: Sch. Des. =Schematic Design, Des. Dev. = Design Development, Cons. Docs. =Construction Documents, Cons.=Construction. *Cons. Phase: The core-periphery structure is rejected and thus no core members are listed.

Network	Sch. Des.	Des. Dev.	Cons. Docs.	Cons.
Project-Level	178	183	244	875
Energy-Efficiency Group-Level	43	44	62	65
Core Members in Analysis	12	11	9	-*
Tier 1 Members in Analysis	7	7	7	5

Table 3-2 lists the regression results of the three social influence analyses. The results show that the fits of all analyses are significant (p<0.001), indicating the existence of a causal relationship between the original and subsequent knowledge transfer. The results also show that project-level exposure is a significant predictor of subsequent group-level knowledge transfer for analysis 2, and 3 (p<0.05). Also, the cross-level influence on knowledge transfer is positive (coefficients ranging between 0.447-1.184). In other words, project-level exposure positively influences group-level knowledge transfer in project teams.

Table 3-2. Regression results of influence model

Analysis	N	R^2	*p*-Value	Variable	Coefficient	St. Error	*p*-Value
Analysis 1	34	0.646	<0.001	Y_{it0}	0.240	0.426	0.577
				Exposure	0.447	0.425	0.302
Analysis 2	39	0.719	<0.001	Y_{it0}	-0.322	0.347	0.360
				Exposure	1.184	0.358	0.002
Analysis 3	48	0.668	<0.001	Y_{it0}	0.144	0.310	0.644
				Exposure	0.677	0.313	0.035

The strongest counter explanation to our inference of influence on knowledge transfer is based on selection of network members. Specifically, that those who already had high levels of engagement may have selected to interact with similar others, negating our interpretation of influence occurring. Our first response is that we controlled for prior rate of behaviors. In fact, Frank and Xu (2020) show that if selection occurs only based on prior behaviors, then controlling for prior behaviors, as we have, removes the bias. Furthermore, we recognize there may still be concerns about selection bias that cannot be attributed solely to the prior behaviors we controlled for. Therefore, we performed sensitivity analysis using KonFound-It causal inference robustness tool (Rosenberg et al. 2022) and quantified how much of the estimated effect of exposure must be due to uncontrolled bias to invalidate the inference (Frank et al. 2013). For analysis 2, to invalidate our inference, 38.787% of the estimate would have to be due to bias. Following Frank et al (2013), this can be interpreted as to invalidate an inference, 15 observations would have to be replaced with cases for which the effect is 0 (Robustness of Inference to Replacement (RIR) = 15).

Within the context of this study, the findings suggest that an individual's exposure to the overall project collaboration places a positive impact on their sharing, disseminating, and inputting of energy-efficiency-related knowledge for problem solving. An exception is Analysis 1 where the exposure's impact was not observed early in project delivery between the periods schematic design and design development.

As the robustness of these three analyses varied but showed evidence of influence, we ran the influence model by stacking the data from three times points to observe the influence occurring throughout the project delivery. To do so, we added dummy variables for the different analysis as seen in the influence model below.

$$y_{it1} = \rho \sum_{j=1}^{n} \left[w_{ij(t0 \rightarrow t1)} z_{j(t0)} \right] + \gamma y_{it0} + Dummy\ 1 + Dummy\ 2 + e_{it}$$

Because of stacking data from three time points, some nodes repeated in the dataset more than once. Therefore, to account for the dependence of the observations, we included the nodes as fixed effects and run mixed analysis. The results showed that the exposure had a positive effect (coefficient= 0.844 and $p = 0.005$) on the subsequent group-level knowledge transfer, controlling for nodes with fixed effects (Table 3-3). We also used random effects with the nodes and the estimate and interpretation were very similar (exposure coefficient= 0.840 and $p < 0.001$) with a smaller standard error (0.215). The coefficient for Y_{it0} below is negative (-0.524), as it is collinear with the nodes as fixed effects. When we repeated the same analysis by removing the nodes as fixed effects, Y_{it0} was positive with a coefficient of 0.036.

Table 3-3. Regression results of stacked influence model with nodes as fixed effects

						95% Confidence Interval	
Parameter	Estimate	Std. Error	df	t	*p*.	Lower Bound	Upper Bound
Intercept	0.155	0.080	63	1.938	0.057	-0.005	0.315
Exposure	0.844	0.290	63	2.912	0.005	0.265	1.424
Y_{it0}	-0.524	0.265	63	-1.979	0.052	-1.053	0.005
Dummy1	-0.032	0.028	63	-1.170	0.246	-0.088	0.023
Dummy2	-0.037	0.026	63	-1.409	0.164	-0.089	0.015

We also performed sensitivity analysis using KonFound-It for the model and we quantified how much of the estimated effect of exposure must be due to uncontrolled bias (Frank et al. 2013). For the analysis where the nodes are fixed effects, to invalidate our inference, 38.358 % of the estimate would have to be due to bias. That is, to invalidate an inference, 38 observations would have to be replaced with cases for which the effect is 0 (RIR = 38) (Frank 2000). We also analyzed the project-level exposure on members of the core using stack data as well as influence with the model below. Because of concerns about collinearity and as indicated by increased standard errors from the fixed effects added, the reported results of these models are without the fixed effects.

$$y_{it1} = \rho \sum_{j=1}^{n} \left[w_{ij(t0 \rightarrow t1)} z_{j(t0)} \right] + \gamma y_{it0} + Dummy\ 1 + Dummy\ 2 + Core + [CE] + e_{it}$$

y_{it0}	Group-level eigenvector centrality of the node *i* at time *t0*, denoting the original potential knowledge transfer of member *i* within the group network.
y_{it1}	Group-level eigenvector centrality of the node *i* at time t_1, denoting the subsequent potential knowledge transfer of member *i* within the group network.
$w_{ij(t0 \rightarrow t1)}$	Project-level interactions received by *i* from *j* during the period of *t0* - *t1*.
z_{jt0}	Project-level eigenvector centrality of the node *j* at time t_0, denoting the original potential knowledge transfer of member *j* in the project network.
$\sum_j^n w_{ij(t0 \rightarrow t1)} z_{j(t0)}$	Project-level exposure, indicating potential influence of project member *j* on group member *i* during the period of t_0 - t_1.
Core	1 for core members, 0 for periphery members
CE	(Exposure -Mean_Exposure) * (Core-Mean_Core)
ρ and γ	Coefficients
e_{it}	Error

As seen in Table 3-4, the result of the analysis showed that influence may be weaker for the members of the core. The core members of the networks were the outliers of the social influence model and the behavior change for them was less compared to the rest of the team. They got influenced less by being exposed to less extreme people. When we controlled the core members, the estimated influence of team members was stronger (coefficient = 1.045).

We performed the same analysis with the stacked data to test whether exposure was, too, weaker for members of Tier 1 and the results, indeed, indicated that influence may be weaker for Tier 1 members (i.e., like core members) (Table 3-5). It should be noted that most Tier 1 members were involved in the core throughout the project delivery and additional members entered and exited the core based on the project needs.

Table 3-4. Regression results for the core members

Analysis	N	R^2	*p*-Value	Variable	Coefficient	St. Error	*p*-Value
1. Stacked Core	121	0.668	<0.001	Y_{it0}	-0.213	0.265	0.424
				Exposure	1.045	0.336	0.002
				Dummy Analysis 1	-0.047	0.031	0.133
				Dummy Analysis 2	-0.028	0.030	0.345
				Core	0.056	0.047	0.238
				CE	-0.296	0.227	0.196

Table 3-5. Regression results of tier 1 members

Analysis	N	R^2	*p*-Value	Variable	Coefficient	St. Error	*p*-Value
1. Stacked Tier 1	121	0.668	<0.001	Y_{it0}	-0.070	0.238	0.771
				Exposure	0.912	0.279	0.001
				Dummy Analysis 1	-0.046	0.032	0.151
				Dummy Analysis 2	-0.026	0.030	0.380
				Tier 1	0.003	0.055	0.964
				TE	-0.136	0.167	0.416

3.6 Discussion

By using social influence mechanisms, diffusion of necessary practices and behaviors can be enabled for better project performance, and yet few studies examined the concept in project teams. Therefore, this study investigated changes in knowledge transfer behaviors of team members that occur through social influence mechanisms as a result of information exchanges between different levels of project collaboration. This research found quantitative evidence that exposure to project-level knowledge transfer exerts a causal influence on group-level knowledge transfer of individuals within project collaborations. The outcomes of this research provide theoretical and practical implications to better understand and implement collaboration and influence mechanisms, especially in complex project organizations.

3.6.1 Theoretical Implications

First, results suggest that knowledge transfer behavior is dynamic and team members tend to share knowledge in the networks as a result of being exposed to the knowledge of others. In parallel with the literature, team members reciprocate the action of receiving by giving in the future (Froehlich and Carbonell 2022) implying that knowledge transfer of individuals might be organized according to evolving project needs (Nonaka 1994).

Second, our findings suggest that individuals' knowledge transfer in their sub-team changes in response to the information acquired from their broader connections. In other words, exposure to diverse information from different social circles and expertise areas within the project is a significant predictor of the subsequent knowledge transfer within a domain group. The results support the idea that every relationship in a network creates an opportunity for the actors to access knowledge (Froehlich and Carbonell 2022). In this paper's context, interacting with influential and central members of the project network positively impacted the knowledge transfer of an individual in the sustainability network and made them more influential in the following episode. The results are in parallel with the argument that being connected to individuals from different social circles and getting novel and diverse expertise promote sustainability knowledge transfer (Granovetter 1973; Henry and Vollan 2014) and the teams with a broad range of connections with other organizational teams might achieve creative and feasible outputs (Kratzer et al. 2010).

Third, opinion leaders (i.e., Tier 1 or core members) received weaker influence and their knowledge transfer changed little over project delivery, compared to other team members. This reflects a paradox that team leaders often have strong exposure, but they are difficult to be influenced during the information exchange with many others in their networks. They are stretched in many directions but they are cautious about changing their beliefs not to lose their positions in the network meaning (Valente 2010). The results support the idea that opinion leaders do not embrace an idea before the majority does and they exercise their influence (Valente and Pumpuang 2007).

Lastly, this study uses eigenvector centrality as a proxy for knowledge transfer behaviors and suggests that eigenvector centrality can be used as a measure of attitude (Brass 1984). To the best of our knowledge, few studies in the project management literature used network properties to evaluate influence mechanisms quantitatively. In parallel with the literature, the study findings suggest that individuals with high eigenvector centrality spread it as an attitude to their connections (Golbeck 2013).

3.6.2 Practical Implications

The findings provide practical implications for project management discipline and complex project teams. Understanding how network structure and the social dynamics of a network mutually inform each other can help project managers develop practical and managerial strategies for successful project delivery. First, team members adopt different behavior patterns from their colleagues in projects. Therefore, project managers should involve key parties in project delivery early in the design phase to promote a cohesive team with goal alignment and achieve higher integration by using influence processes (Franz et al. 2017; Mollaoglu-Korkmaz et al. 2013).

Second, individuals with a higher influence and central position spread their attitudes to the people they interact with and help propagate innovations by influencing others (Henry and Vollan 2014). Therefore, project managers should give attention to promote interactions between opinion leaders and especially peripheral members to: (1) Accelerate the diffusion of the necessary information and behaviors from opinion leaders to all project members to implement innovation (Lee et al. 2018); and (2) Increase cohesion and knowledge transfer by using influence processes as increased centrality has a positive effect on performance (Sanchez et al. 2017).

It is also observed that the attitude change was less for the opinion leaders. Even though this can give stability to the system in the project delivery, it might also reduce the innovative capacity of the team. While information diffusion from highly influential members to peripheral members can be vital for goal alignment, project managers should recognize the importance of peripheral members to bring innovative ideas needed for sustainability. Therefore, project managers should involve peripheral members in the collaboration networks proactively (Duva et al. 2020; Zhao et al. 2021) and especially early in the project delivery to ensure influence, as early design phases have a greater impact on project outcomes and success (AIA 2007).

3.7 Conclusion

Complex project teams are composed of individuals with diverse backgrounds and competencies, who work towards a shared goal. Coordinating the efforts of different components is harder while delivering sustainable projects due to the increased number of parties, requirements, and technical components. Team members should collaborate efficiently to fulfill the increased expectations and diffuse desired practices by interacting.

This study contributes to the knowledge of organizational theory by finding quantitative evidence that diverse project-level knowledge transfer impacts the group-level knowledge transfer as a result of social influence mechanisms. Results show that knowledge transfer is dynamic throughout the project delivery and team members change behaviors as a result of their interactions. Also being exposed to individuals from different social circles with different expertise and high eigenvector centrality positively impacts the eigenvector value of an individual in the group-level network and makes them more influential in the following time. Opinion leaders in the networks change their attitudes less compared to the rest of the team and they exercise their influence on others. During the early stages of the projects, the influence might not occur due to a lack of deep knowledge transfer. Moreover, the network properties can be used to evaluate behavioral changes such as eigenvector centrality.

Limitations exist in the study, which can be addressed in future research. The scope and generalizability of the findings might be limited due to the use of a single, medium-size case study. Even though we identified a causal relationship between project-level and group-level knowledge transfer, we also acknowledge that there might be other confounders for our causal estimates. While email exchange data showed to be representative of project team communication, the influence was evaluated using the email exchange data without examining the impact of different communication methods such as face-to-face interactions, online meetings, or text messages. Future research can extend this work and explore the advantages and disadvantages of the difference in the influence patterns of opinion leaders for the network functioning. Nonetheless, this study sheds light on the social influence model that can be applied to networks in any complex project team.

3.8 Acknowledgements

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4 A FRAMEWORK FOR SOCIAL NETWORK INTERVENTIONS IN AEC TEAMS

4.1 Abstract

Successful execution of a project depends on efficient collaborations among a diverse set of actors and organizations. Establishing efficient collaboration networks is vital to channeling necessary expertise to achieve desirable outcomes. Network interventions describe the process of using network-supported strategies to enable knowledge sharing and coordination critical for network performance. However, there is a lack of intervention studies in the Architectural, Engineering, and Construction (AEC) domain. To fill this gap in the literature, this study uses social network analysis (SNA) and mixed methods in the pursuit of developing a rigorous intervention protocol for the AEC teams. To achieve the study goals, the research team examined the performance and communication trends of an AEC project team during project delivery in the light of the literature to inform network interventions. After vetting the developed strategies through interviews with select project leaders, interventions were finally presented to the whole project team for further verification and feedback. The results contribute to the body of knowledge by providing an intervention framework for AEC teams and implications for practitioners in selecting and assigning experts in key roles and positions in projects as well as managing team communications and networks in a dynamic manner during project delivery for the improved team and project performance and resilience.

4.2 Introduction

Architectural, Engineering, and Construction (AEC) teams consist of a wide range of experts, organizations, and stakeholders working under pressure to meet project specifications and client requirements. The successful execution of a project relies upon productive collaborations among experts from various disciplines (Cross et al. 2006; Duva et al. 2020). However, due to the complex features of AEC projects, such experts' abilities to successfully integrate their knowledge and skills frequently encounter challenges (Korkmaz and Singh 2012).

To eliminate the challenges of complexity, social network analysis (SNA) emerged as a robust tool to depict and systematically assess the topology of interactions in AEC collaboration networks (Hanneman and Riddle 2005; Kereri and Harper 2018). More importantly, SNA can help identify constraints in collaboration networks, find appropriate solutions at critical points to mitigate fragmentation problems (Lin 2015), and improve knowledge transfers and project performance by using network interventions (Cross et al. 2002).

Formally, "network intervention" describes the use of SNA-driven strategies to generate social influence, facilitate behavior change, and improve performance (Valente 2012) by improving network effectiveness (Cross et al. 2006). However, there is a lack of intervention studies across project network domains that can help improve the functioning of project team networks.

To fill this gap in the literature, this paper studied network intervention phenomenon in the context of AEC project team networks via the lens of Cross et al. (2006)'s framework to understand the functioning of AEC project team networks. Specifically, the study aimed to develop a rigorous intervention protocol by observing and leveraging an in-depth case study in the light of the recent AEC literature to improve knowledge transfers and collaboration in AEC teams. The research team conducted vetting sessions through interviews to evaluate the quality of preliminary network interventions before sharing them with the larger project team (Pinto Nunez et al. 2018). The study contributes to the literature by providing an intervention framework to improve system functioning and resilience based on evolving project needs pertaining to making assignments, tracking overload, increasing engagement, and addressing fragmentation problems.

4.3 Literature Review

4.3.1 Networks and Interventions

Network interventions indicate a series of coordinated efforts designed to enhance knowledge sharing and coordination to achieve improved performance and desirable outcomes in social systems (Valente 2012). SNA is an assessment method of relational structures in collaboration networks (Butts 2008), which is also helpful in determining actionable points and operationalizing collaborative patterns (Maya-Jariego and Holgado 2015). By using SNA, different network configurations and metrics can be identified that inform interventions (Frank et al. 2022).

To elaborate, network configurations such as a core-periphery and subgroup structures emerge according to communication patterns and serve different purposes in networks (Figure 4-1). In a core-periphery structure, the core consists of a small number of members who interact frequently, whereas the periphery includes members who have limited connections which are primarily to the core (Borgatti and Everett 2000). A member is more (core) or less (periphery) central to the network based on their interactions with other team members. Subgroup structure represents the existence of densely connected groups of individuals which have only sparser connections between groups (Frank 1995). Additionally, network metrics help mathematically evaluate network configurations, overall team collaboration, and individuals' roles and leadership positions in networks. Objective evaluation of network configurations and network metrics such as density and cohesion at the "team level" and degree and betweenness centrality at the "individual level" (and evolutions thereof) can provide basis interventions (Cross et al. 2008) in pursuit of improved collaboration networks and performance.

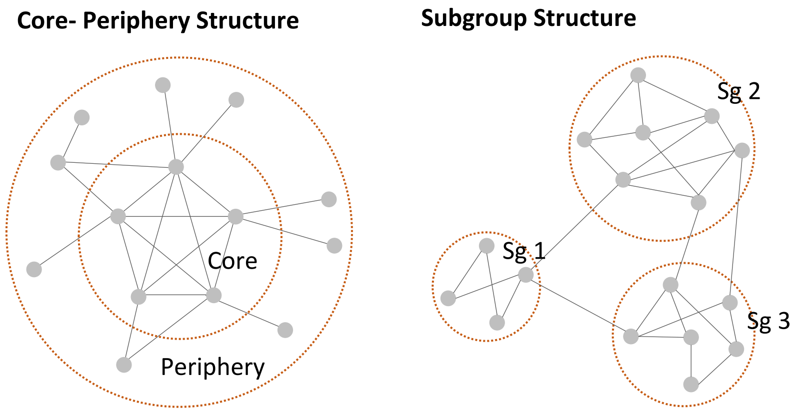


Figure 4-1. Core-periphery and subgroup (Sg) structure

According to Cross et al. (2006), assessing the following can guide network interventions: (1) Identifying *central people* in networks to balance communication and information overload; (2) Finding *brokers* to help diffuse knowledge; (3) Including key *peripheral players* to integrate their unique expertise and skills; (4) Targeting *fragmented points* in the networks to fill structural holes; and (5) Improving *external connectivity* by activating boundary spanners. Building upon (Cross et al. 2006), Valente (2012) categorizes network interventions targeting: (a) *Individuals* - empowering selected individuals as champions of behavioral changes; (b) *Segmentation* - focusing on a group of people to induce change at the same time; (c) *Induction* - triggering peer-to-peer interaction to enhance information and behavioral diffusion focusing on existing nodes (e.g., individuals) and their ties (e.g., relationships); and (d) *Alteration* - adding or deleting nodes in the network and rewiring ties between nodes to increase performance and efficiency.

4.3.2 Network Interventions in AEC Teams

The need for repeatable intervention protocols across project network domains is prominent to help contribute to the functioning of project teams by engaging networks and individuals as a part of larger teams (Matous et al. 2021). This gap is even wider for the AEC domain. In AEC project teams, where knowledge transfers are crucial, informal and formal networks (i.e., emergent communication networks versus organizational assignments) do not necessarily overlap or stay static, and collaboration priorities change (Garcia et al. 2021), use of SNA shows great promise to optimize team dynamics across multiple organizations (Cross et al. 2014). However, most intervention studies focus on team building without much insight into performance values and utilization of SNA.

Chinowsky et al. (2011) demonstrated the early potential of network intervention in AEC teams, presenting a project network interdependency alignment approach to identify neglected and ineffective knowledge exchanges. While this approach can help project managers proactively avoid such deficiencies, the study did not specify intervention strategies and protocols in cases where such deficiencies occur. In a key study, Pollack and Matous (2019) conducted SNA for three months to examine the patterns of communication in a project team and inform team-building interventions. They aimed at increasing personal communication comfort and bridging structural holes in the networks with their interventions and observed a significant increase in personal and work-related communication frequency and network density. Pirzadeh et al. (2021) proposed a framework to investigate interdependencies and social interactions for design teams. They found that internal and external experts and the prevalence of closure and reciprocity in networks are helpful for effective design solutions and can be monitored to inform possible intervention strategies. In the context of megaproject networks, Shi et al. (2022) highlighted the need for network controls and optimization strategies, which included the identification of impaired ties and nodes, dysfunctional networks, and implementation of network interventions. Recent research revealed many insights into AEC project team networks including inconsistencies between organizational and communication networks and how to address them (Zhao et al. 2021), the impact of network topology and metrics on performance (Duva et al. 2020), and the importance of triadic closures in network transitions (Garcia et al. 2021).

While the studies above set the stage for network interventions, the network intervention phenomenon remains yet understudied in the AEC domain. To fill this gap, this study conducts a rigorous longitudinal study of AEC project networks in the light of the literature and develops a framework for AEC project teams that can be used as a foundation for timely and intentional network interventions during project delivery to improve system functioning and resilience.

4.4 Point of Departure

4.4.1 Considerations for AEC Teams

Two conditions unique to project teams exist and must be considered for network intervention adoptions in the AEC domain. First, they go through cyclic phases, called *progress loops*, where each phase becomes the input for the successor phase (Garcia et al. 2014; Marks et al. 2001). Progress loops correspond to project needs and contribute to the evolution of network structures. A typical AEC project goes through schematic design, design development, construction documents, and construction episodes. Moreover, based on project progress such as cost, schedule, and/or scope changes, a project might have many more turning points and might be further broken down into shorter time intervals. Depending on the nature of these progress loops (i.e., episodes and time intervals), the need for coordination and/or deep knowledge sharing might interchangeably become a priority for any project (e.g., planning and programming versus construction phases), leading to a variety of emergent collaboration network structures such as core-periphery and subgroups (Garcia et al. 2021).

Second, emergent collaboration networks in AEC project teams and individuals' positions in those networks might not align with their formal organizational structures (Zhao et al. 2021).

For example, a general contractor's project manager, one of assigned leads in an AEC project organization, is highly likely to be one of the core members in collaboration network during the construction phase, while this might not be necessarily the case during design phases. Figure 4-2 shows an example of changing core-periphery membership from design to construction nested in organizational structure (developed based on (Garcia et al. 2020; Mollaoglu-Korkmaz et al. 2014).

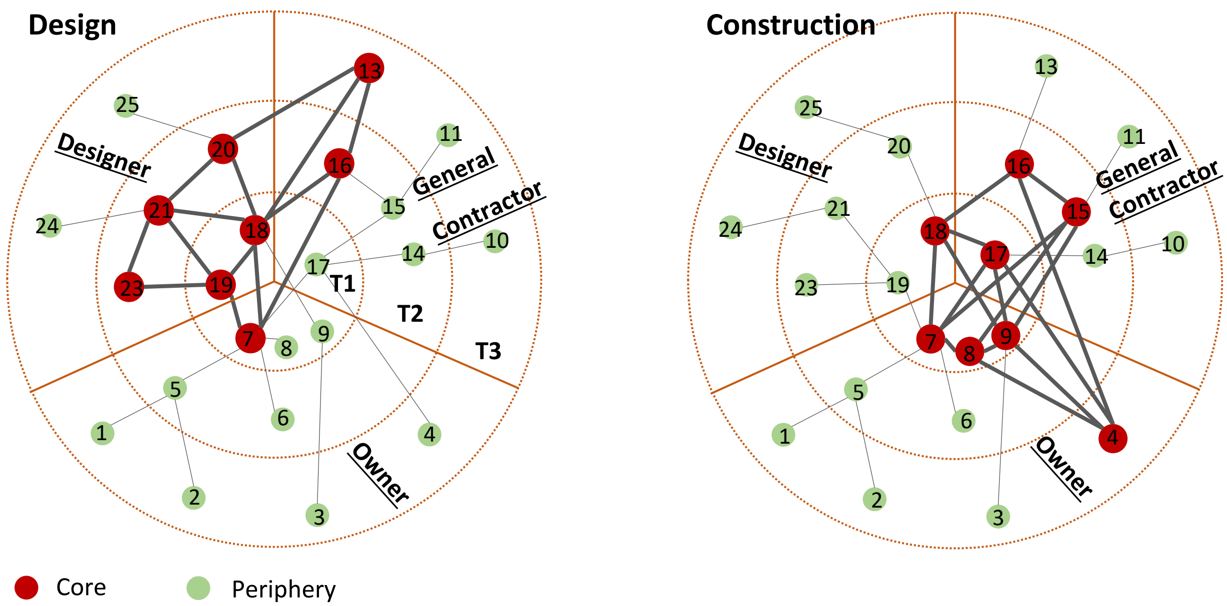


Figure 4-2. Change of core and periphery members in collaboration networks from interval 1 to interval 2 depicted over the project's organizational structure. Note: T1= Tier 1, T2= Tier 2, T3= Tier 3. Numbered nodes denote individuals.

Further elaborating on this concept, organizational structure in project teams follows contractual ties between parties and most frequently includes three main roles (i.e., owner, general contractor, and designer) across three tiers: *Tier 1* includes project leads, holding decision-making authority in the day-to-day project operations; *tier 2* consists of team members in tier 1 members' home organizations; and *tier 3* encompasses all other individuals associated with the project outside of the main organizations such as subcontractors, vendors, consultants, and other stakeholders. An organizational network for a project team is based on contracts and assignments, and for the most part, is static. However, any member of a project team can be in the core or periphery and switch across different subgroups based on their communication behaviors at any given time in project delivery regardless of role, tier, and expertise area. Even though different contractual arrangements impose varied communication links and organizational structures at the beginning of delivery process (Franz et al. 2018), as the project continues, new collaboration patterns emerge based on project needs (Garcia et al. 2021), team member characteristics (Chinowsky et al. 2018), and other factors such as trust or previous experience (Chinowsky et al. 2008).

4.4.2 Adoption of Network of Intervention Framework

Studying AEC projects, in the light of progress loops and misalignment between the organizational and collaboration networks as described above, we adopt *Cross et al. (2006)'s* network intervention framework. This section discusses the framework elements, namely, central connectors, brokers, peripheral players, fragmentation points, and external connectivity

Central connectors are the most central individuals in a network with the highest degree centrality, which is calculated as the total number of connections linked to a node (Freeman 1978). With the simplest example, if a project manager has connections with a designer, a mechanical engineer, and an electrical engineer, this individual has a degree centrality of three in this network. In AEC teams, tier 1 members, who are assigned leads, are potential central connectors and should be the primary focus of analysis. Additionally, core-periphery analysis help identify central individuals to the project team regardless of formal appointment (Borgatti and Everett 2000). Carrying the most direct connections, central connectors play critical roles in a network and should be targeted to improve the diffusion of information and engagement. Interventions should also address their overload to improve network efficiency and resilience (Cross et al. 2006).

Brokers are knowledge leaders in a network who are strategically on the shortest path between unlinked team members and are ideal for disseminating knowledge (Cross et al. 2006). Betweenness centrality (i.e., calculated by counting the number of geodesic paths that pass through a node)(Freeman 1978) is often used in the literature to identify brokers in a network (Long et al. 2013; Marco et al. 2010). For example, a mechanical engineer working for the primary designer in an AEC project may communicate with an external mechanical design consultant and can function as a broker between the consultant and design leads from their organization.

Peripheral Players are loosely connected members in a network with specific skills, resources, and expertise for a project and are important in bringing novel information (Cross et al. 2006). Their integration can be critical for an AEC team in achieving collaboration (Zhao et al. 2021) and improved project performance (Garcia et al. 2020). For example, even a short involvement of a peripheral governmental representative in AEC project collaboration might bring the novel and necessary information relating to planning and programming that the rest of the design team is dependent on to complete their work.

Fragmentation Points indicate the gaps in networks arising from a number of variables including but not limited to expertise differences, hierarchy and power dynamics, and working in different locations (Cross et al. 2006). Such conditions are highly relevant to AEC project teams. For example, if a furniture vendor contracted to a general contractor is not copied in relevant e-mails by the designer, the project network relies on the general contractor as an information broker. If the general contractor does not connect the designer and furniture vendor in resolving relevant project issues; the vendor would be fragmented from the rest of the network, which inhibits problem-solving and successful execution. Even though structural holes can serve networks in eliminating redundant information and potential overload; having disconnected parties might inhibit the alternative options and innovation capacity in networks (Burt 2004).

External Connectivity can enable learning from external stakeholders in networks (Cross et al. 2006). AEC project team members are often geographically and organizationally dispersed. Boundary spanners that cross technical, geographical, and cultural boundaries can facilitate effective knowledge transfers with external stakeholders and help improve project performance (Duva et al. 2020; Marco et al. 2010; Ramalingam and Mahalingam 2011). For example, a mechanical engineer working for the general contractor can reach out to the designer's mechanical engineer to get an information needed by crossing the organization's boundaries under deadline pressures to avoid schedule slippages instead of depending on project managers.

4.5 Methodology

The research team followed an exploratory approach to identify trends in team and project performance and corresponding network patterns. In this process, we first used qualitative and quantitative methods to examine performance and communication trends during project delivery and determined slowdowns, congestion points, and highlights in the networks. We, then, studied the network trends via the lens of Cross et al. (2006)'s framework and developed the preliminary interventions. Finally, we collaborated with key project members and conducted interviews for vetting the developed intervention strategies before sharing them with the team members.

4.5.1 Data Collection

The research team collected data from an institutional major renovation and expansion project during its delivery for two years starting from schematic design until substantial completion (Figure 4-3). The project had a budget of $20 million and was delivered via construction management at risk. The project team involved three main roles (i.e., owner, designer, and general contractor) and sub-teams including subcontractors, vendors, governmental institutions, and consultants. Throughout the project delivery, more than 1000 team members were involved based on the project needs and schedule. We longitudinally collected archival (i.e., meeting minutes and project documents shared on online document sharing platforms), survey, and communication data (i.e., e-mail exchange, and observational), and conducted interviews to develop the AEC network intervention. Using different sources of data helped us enable data triangulation.

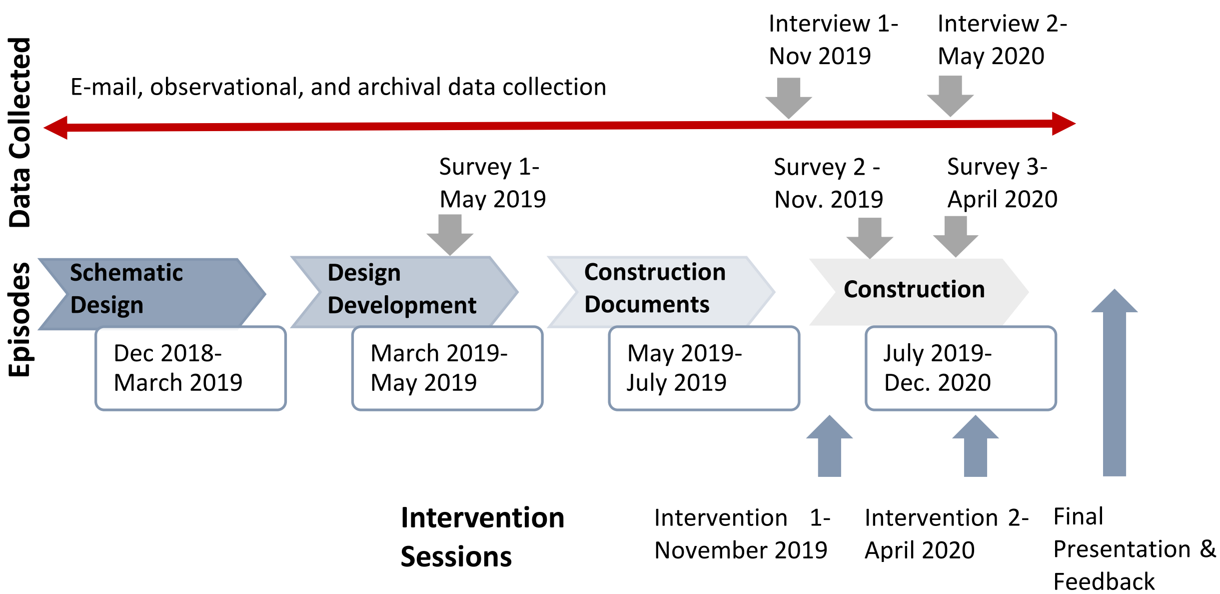


Figure 4-3. Timeline of data collection and interventions in the case study

Archival data (i.e., meeting minutes and project documents shared on online document-sharing platforms) aided determination of the project's progress loops (Garcia et al. 2014; Marks et al. 2001) and create a timeline for data analyses. First, we determined the start and end dates of the main project episodes (i.e., schematic design, design development, construction documents, and construction) and then further broke them down into monthly time intervals based on the cost growth, scope revisions, and major construction milestones as the key metrics. This process revealed 19 intervals, each spanning four to eight weeks. We also used archival data to calculate project performance as explained in the data analysis section.

Using survey data, we measured individual performances three times throughout the project delivery. In the surveys, team members who gave consent to participate in our research were given the names of the top ten people that they communicated with the most frequently. Then, using a four-point Likert scale, participants were asked to evaluate their peers through questions relating to contribution to project execution, communication and coordination skills, adaption to changes, and innovation (e.g., completed tasks on time, and communicated effectively with the team members). Surveys included demographic questions such as experience in the AEC industry and with similar projects, areas of expertise, and education level to gain further insight into the project network.

To study team communication, we first collected e-mail exchange data consisting of e-mail headers (i.e., subject, to/from, size, and date). Even though e-mail data extraction is an onerous task, it eliminates self-reporting bias and provides insight into actual communication flows (Kadushin 2012; Quintane and Kleinbaum 2011). Moreover, the project communication protocols required team members to send follow-up e-mails for documentation purposes if they use a different communication media. Second, two coders from our research team attended the weekly project team meetings and systematically recorded the number of “information given” by each individual (e.g., in the shower area, we have a steam room which will all be tile) (Frank and Zhao 2005).

Lastly, we conducted interviews with project team leaders to refine intervention strategies.

4.5.2 Data Analysis

To evaluate team performance, we calculated survey scores for individuals based on peer evaluations (i.e., by taking the average of the scores given by the most frequently communicated peers). We used archival data (e.g., meeting minutes) to calculate project performance. More specifically, we identified project activities/issues, the lead party responsible for those (i.e., owner, designer, general contractor), and the duration for their resolution. We then calculated project performance during delivery for the whole project team and lead roles, using the percentage of resolved issues over ongoing issues per interval and progress loop.

We used e-mail exchange data to determine the nodes and tie strengths in the project networks and assigned 3, 2, and 1 as tie weights for daily, weekly, and monthly communication between nodes. Gephi software was used to visualize interactions based on the project's organizational structure and calculate network metrics such centrality values of project team members. The archival data helped us determine the organizational assignments (i.e., role, tier, and expertise) and therefore, the positions of individuals in the organizational networks. To evaluate the collaboration structure, UciNet software was used in determining the core-periphery structures (Borgatti and Everett 2000), and KliqueFinder software in determining subgroup structure, which maximizes the concentration of close interactions within subgroups versus between subgroups (Frank 1995). E-mail exchange data and its representation of the overall project communication network were verified via (1) comparing whether the top ten people determined before the questionnaires reflect the communication patterns of the individual and (2) presentations of sociograms in individual interviews prior to each intervention.

Observational data also were incorporated in sociograms as node attributes and used for calculating individuals' engagement levels. More specifically, node sizes represented the frequency of information given by individuals in the face-to-face team meetings as recorded by the research team. Thus, the larger a node in sociograms, the more engaged the individual was in team meetings. Also, the total amount of information given was calculated for each interval as a measure of team engagement. We calculated the interrater reliability for the first 21 meetings out of 93 for all pairs of coders from the research team and stopped seeking further evidence for coding reliability as a strong correlation was achieved (i.e., the average correlation was $r= 0.89$).

Using network visualizations and team and project performance trends over project delivery, we determined possible misalignments, bottlenecks, and strengths and weaknesses in the networks; and developed intervention strategies accordingly using Cross et al. (2006)'s framework. Before sharing interventions with the project team members, we conducted vetting sessions through interviews with tier 1 project team members to tailor the intervention strategies (Cross et al. 2014; Pinto Nunez et al. 2018). We conducted five interviews (i.e., a total of three project managers from the owner and general contractor, one designer, and one user group representative from the owner) before the first intervention and two interviews (i.e., a total of two project managers from the owner and general contractor) before the second intervention. Each interview took approximately one hour, was recorded, and transcribed afterwards.

The intervention sessions were conducted in December 2019 and April 2020 (Figure 4-3). Two of the authors guided the process and presented intervention strategies to project team members. Eight to ten people including upper management representing the owner, designer, and general contractor roles attended the sessions. Each session took one to two hours. In accordance with the Institutional Board Review guidelines at Michigan State University, all data and findings were presented in an anonymous and aggregate form. While reporting findings, personal identifiers, such as organization, tier, or expertise area of the individuals, were altered purposefully to satisfy the anonymity of participants without compromising the data quality (Parry and Mauthner 2004). At the end of the intervention sessions, we conducted surveys and facilitated feedback sessions to collect further evidence for the use and impact of the interventions.

4.6 Results

4.6.1 Performance and Communication

Descriptive analysis of surveys showed good team performance throughout project delivery (i.e., the average performance of individuals for three-time points was 87.5%, 82.5%, and 90%, respectively). Project performance (i.e., calculated as the percentage of issues resolved over the number of ongoing issues in any given progress loop) ranged between 23.3% and 80.9%, while it was 67.4%, 62.3%, and 44.1%, for the designer, owner, and general contractor respectively, considering lead roles during the entirety of the delivery process.

Figure 4-4 shows the trends in project performance as well as team engagement (i.e., the total number of e-mail exchange data and information given in the face-to-face meetings for an interval). Trends showed a link between the average team engagement and issue resolution rate. For example, project performance and engagement both dipped in design development 1 (DD1), while they both peaked with a two-week-lag in between during construction documents 1 (CD1) and construction 8 (C8) intervals. The only exception to this alignment of performance and engagement trends was early in the construction phase (C1-C4), where the inconsistency might be attributed to changing project needs, change in the communication lead (designer versus general contractor), and dynamics due to transition from design to construction phase. With the involvement of new individuals in the construction phase, we observed the core-periphery structure dissolved and evolved to a subgroup structure (Frank 1995).

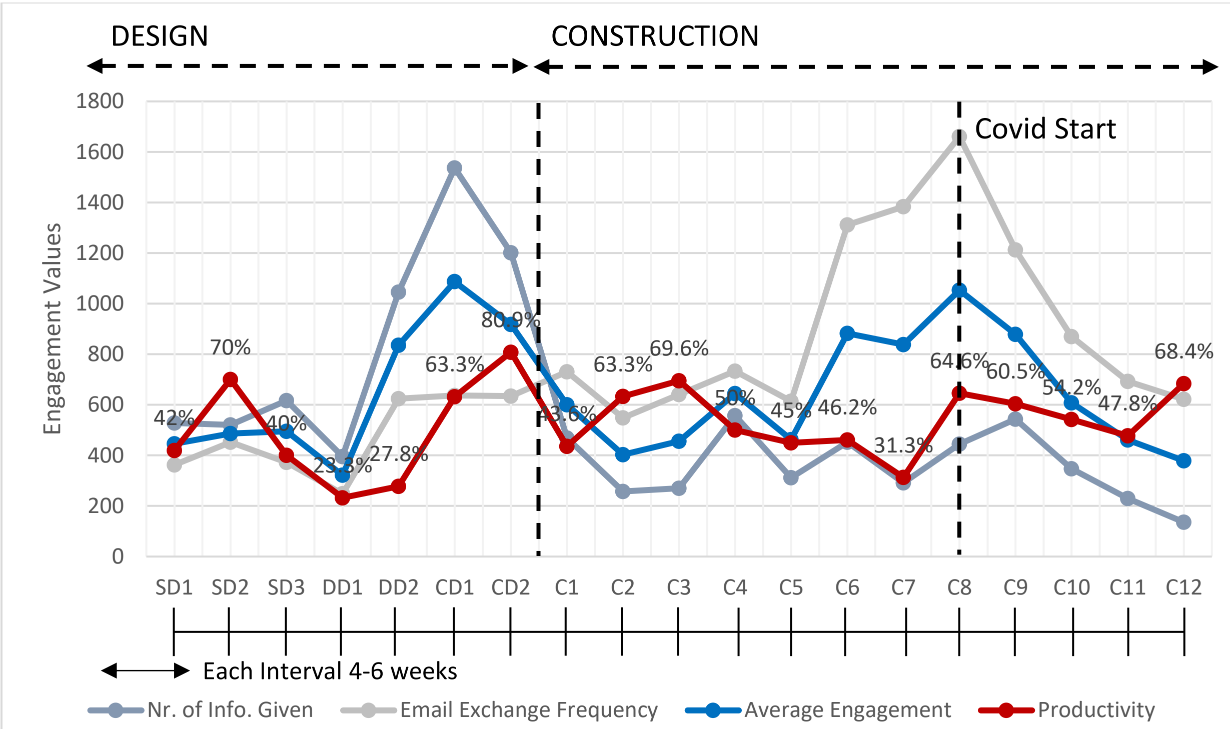


Figure 4-4. Engagement vs. Project Performance. Note: Drastic increase in e-mail exchange frequency in C8 corresponds to the COVID-19 shutdown and off-site working conditions. Note: SD= Schematic Design, DD= Design Development, CD= Construction Documents, and C= Construction.

Based on the highs and lows of performance and communication trends during project delivery (using issue resolution rate and SNA metrics) and potential links among them; we focused on differences in the communication networks (using sociograms in given intervals) for the owner, designer, and general contractor roles, and interpreted the network findings.

4.6.2 Network Observations

Following (Cross et al. 2006)'s framework, we observed the following network characteristics.

Central Connectors: Tier 1 members emerged as the central connectors with the highest degree centrality values based on e-mail exchange data (e.g., for the schematic design, the average degree for the whole team was 8.45, whereas it was 85.57 for the tier 1 members, ranging between 34-126).

Based on the sociograms, we observed two assigned leads in the designer's tier 1 throughout the project delivery, where both leads had more than 15 years of industry experience and worked on more than 10 similar projects, as reported via surveys. One lead coordinated the project communication, while the other lead provided technical expertise. They actively functioned in project communication in the face-to-face meetings and were involved in the network core throughout the project delivery based on UCINET results. The owner started with two leads in tier 1, however, one lead left the project (i.e., staff turnover) after the construction documents episode. Both leads were highly experienced (i.e., more than 15 years of experience and worked on more than 10 similar projects), active in face-to-face meetings, and in the network core. Even though the general contractor had two assigned leads in tier 1, the lead with high experience (i.e., more than 15 years of industry experience) did not attend the face-to-face meetings after DD and left the network core based on communication frequency. The lead with relatively less industry experience (i.e., 5-10 years) actively functioned in the communication network and remained in the network core.

Accordingly, the active and experienced two-lead structure in tier 1 emerged as a potential explanation that might have helped the designer achieve better performance compared to the general contractor during project delivery. Having only one person in owner tier 1 did not significantly impact the performance of the owner (i.e., 62.3%), as the owner never led the project team communication. Having one active lead in tier 1 might have caused unbalanced workloads in general contractor and owner based on their connections and node size (Figure 4-5-A). Especially, the overload on tier 1 of the owner due to personnel and phase transition might be seen in Figure 4-5 between DD1 and C1 intervals. One interviewee reported on the personnel turnover in owner tier 1 accordingly:

"I am really seeing a difference in organization and leadership with [this individual] gone. It has been a learning curve for me changing in the middle of the project."

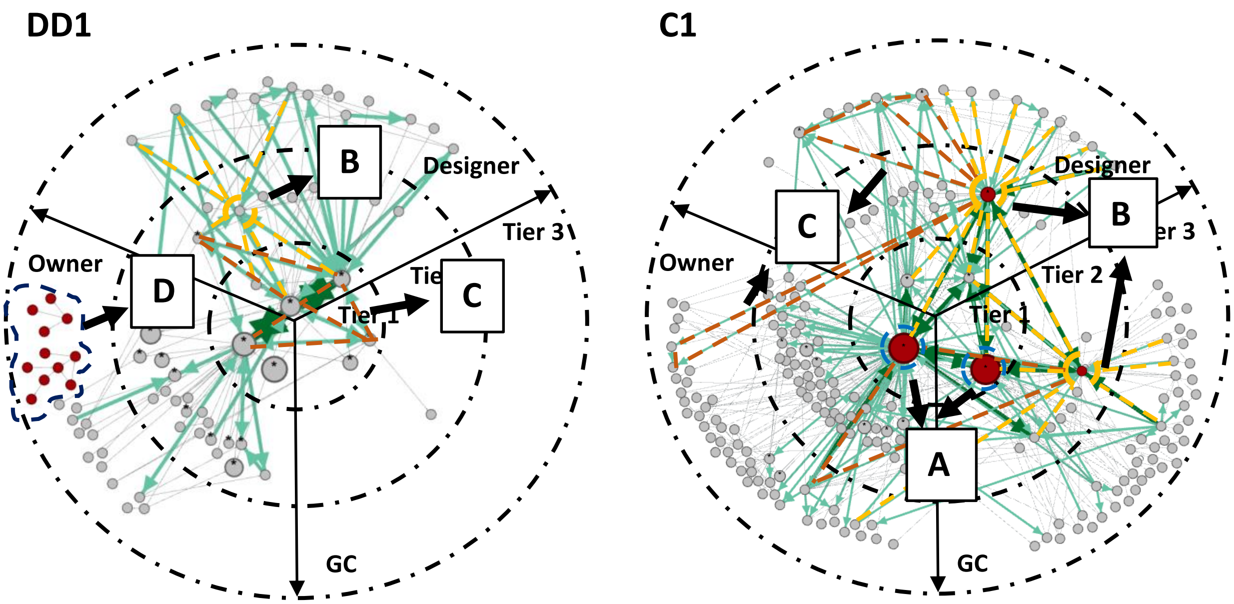


Figure 4-5. Sociograms depicting network observations: A: Overload on central connectors, B: Brokers, C: Network fragmentation due to lack of a broker. Note: DD1-Design Development interval 1, C1-Construction interval 1, GC- General Contractor

Brokers: We observed that two tier 2 team members, one under the designer and the other under the general contractor emerged as information brokers (i.e., design development 1 and construction 1 phase respectively) with high centrality (e.g., in construction 1 interval, in a network of 200 people, two brokers had the highest third and sixth betweenness centrality and the highest 5^{th} and 3^{rd} degree centrality, respectively). They were in the network core after they were involved in the project team. They were highly active in diffusing information upwards and downwards in the project organization (Figure 4-5-B).

Before the involvement of these brokers, strong triadic closures, which facilitate knowledge transfers, were mostly limited to tier 1. After the involvement of the brokers, triadic closures expanded to tier 2, and tier 3 members as seen in Figure 4-5-C. Moreover, the broker of the designer had longer experience in the industry compared to the general contractor's broker (i.e., more than 15 years and 1 year, respectively) and was involved in the project as early as design development 1 interval (DD1). Early involvement and having a transition period until the designer's broker actively started bridging different parties of the network might have contributed to better team performance for the designer.

In the analyses for the case study project, the lack of a tier 2 broker in the owner role placed the entire communication load on the project lead and created a hierarchical communication structure. This situation did not impact the performance of the owner, as the owner did not spearhead the project communication coordination (i.e., designer during the design phase and general contractor during the construction phase). However, such conditions may result in negative consequences and can affect the project network resilience adversely if the team leader is unable to serve as the hub of information.

On having communication support, one interviewee reported:

"Coordination falls on [communication support]. [This person] communicates both up and down [Tier 1 and 3] making sure that we are either involved in meetings if necessary or filters info from/to consultants."

Another interviewee supported this finding accordingly:

"Yeah, I have been leaning on [the communication support] in getting answers instead of [the lead]. In my mind, [the communication support] is secondary but a lot of the phone conversations, explaining what should be done, or a new detail, items, tasks... I like to get things answered quickly. I think why not to go to [the communication support] directly."

Peripheral members: Analyses demonstrated that the lack of peripheral members impaired the pace of issue resolution. For example, during the design development 1 interval, where the team performance was the lowest, engagement of the peripheral experts in the project network and face-to-face team meetings was lowest. Additionally, the composition of the core was not diverse with the involvement of only four tier 1 members without the involvement of peripheral members in active collaboration.

***Fragmentation points*:** During project delivery, experts, especially from tier 3, entered and exited the project network on a need basis depending on the phase of the project, where the most fragmentation occurred. We observed that due to expertise differences, a group of individuals formed a clique in the network, where they were highly connected to each other while being disconnected from the rest of the network. Network fragmentation mostly occurred under the owner, as seen in Figure 4-5-C, due to a lack of ties connecting tier 3 to tiers 2 and 1.

External Connectivity: Like peripheral members, external connectivity and boundary-spanning ties bring novel information and enhance innovation (Marco et al. 2010). The leads and broker under the designer role were involved in interactions within and across their roles and tiers more compared to those under the general contractor role as seen in the construction 1 interval (C1) in Figure 4-5, which might have helped achieve better performance.

4.6.3 Intervention Framework and Feedback

Table 4-1 summarizes the intervention framework and strategies developed for the AEC teams based on the observations and interview feedback presented above.

Table 4-1. Social network intervention framework for AEC project teams (Adopted from Cross et al. 2006)

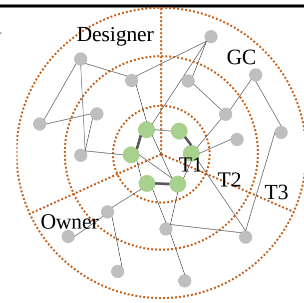
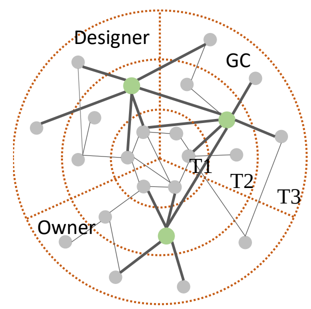
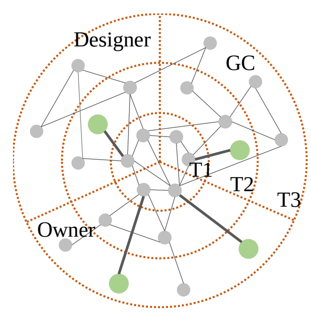
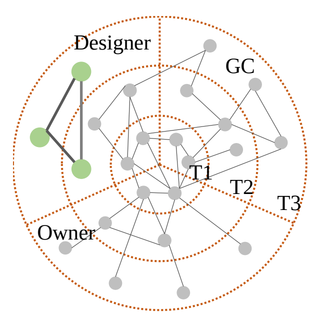
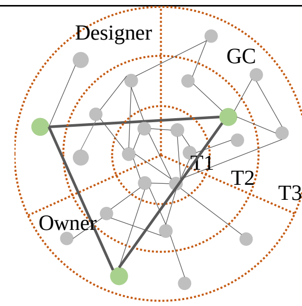
Network Element in AEC Teams	Importance	Possible Threats	Strategy for AEC Project Teams	Network Visualization
1. Teams of Two as Central Connectors	Critical with the most direct connections; thus, should be addressed to improve engagement	Likely to experience communication overload if not appropriately supported in the networks	• "Communication and technical leads" in tier 1 as teams of two per role • Qualification-based selection-prior experience • Continuing engagement of the leads. • Balanced leads for network resiliency.	
2. Communication Support as Brokers	Informal informational leaders who are on the shortest path between others and are ideal to diffuse information	Likely to experience structural holes and delays in getting necessary information if missing a broker	• "Communication support" in tier 2 connecting tiers, roles, and experts • Empowering a broker in designer starting with design phase and in GC starting with construction	
3. Peripheral Players	Individuals with under-used and novel skills, expertise, and knowledge	Likely to experience information redundancy if peripheral members are not involved	• Expertise integration from the "peripheral members" within or outside of the organization • Inviting them to face-to-face meetings for planned times based on the needs	
4. Targeted Involvement for Fragmentation Points	Fragmentation points are gaps in the networks due to expertise differences, hierarchy, or location	Likely to have disruptions in knowledge transfers if not addressed	• Targeted involvement of experts by activating the brokers (i.e., communication support) in tier 2 to promote necessary expertise	

Table 4-1 (cont'd)

5. Boundary Spanning for External Connectivity	Connecting external stakeholders, who are technically, geographically, or culturally dispersed	Likely to experience information redundancy, lack of expertise diversity, and innovative solutions	• Active engagement of the team members from different roles/tiers and expertise and enabling boundary spanning	

1. Teams of Two as Central Connectors: In tier 1 of each role, it is ideal to work in teams of two, where one person is the "Technical Lead" making decisions and the other person is the "Communication Lead" facilitating key information exchange among relevant areas of expertise to support the technical lead closely. Both individuals should be experienced in project-specific technical domains. Participating roles should ensure continued engagement of technical and communication leads of two in tier 1 throughout project delivery but especially during the phases, where they spearhead the team communication. Having a team of two eliminates communication overload and increases network resiliency during personnel and phase transitions. When absent, communication overload might occur. It is highly beneficial if at least one of the leads under a given role has prior experience with leads under other roles, as it was observed that prior working experience can reinforce trust and help improve project team efficiency.

Additionally, personnel changes are common in project teams. Before personnel transitions during project delivery, especially for the high influence roles having an overlap period between the people that transition in and out of the project team to transfer the necessary know-how and mitigate negative impacts is helpful. Moreover, phase transitions should be taken into account as well. While the project moves into a new phase (e.g., from design development to the construction documents episode), the communication network does not necessarily follow the same progress.

During transitions, team members might become overloaded taking on new roles in addition to continuing ones.

2. Communication Support as Brokers: Organizational assignment of a “Communication Support” in tier 2 as a broker to assist Communication Lead in tier 1 is recommended, especially in designer and general contractor roles, who spearhead the communication coordination of projects (i.e., design and construction phases, respectively). Such brokers help bring timely input and prevent communication overload in tier 1. In the lack of communication support, structural holes and network fragmentations might occur as seen in Figure 4-5. Involvement of communication supports also strengthens the triadic closures (i.e., complete ties among three actors) across tiers and roles.

3. Peripheral Players: Central connectors (project leads in tier 1) and brokers (communication support) should effectively engage with peripheral players (team members in tier 2 and 3 such s consultants …) to leverage the knowledge flows. Instead of relying solely on e-mail communication and copying peripheral members on e-mail threads, project leads should consider inviting them to face-to-face meetings for targeted discussions for a limited and planned time to protect them from communication overload. One of the interviewees reported on having peripheral members in the face-to-face meetings that:

> *“...I think it is trying to optimize and recognize that they have a busy schedule, and you don’t want to sit through 3 hours design meeting. And I can get some information through them, and they don’t need to sit in the meetings. I can get the little components.”*

4. Targeted involvement of related expertise areas across should be ensured to eliminate fragmentation points in the project network and integrate necessary expertise. Especially communication supports in tier 2 should find the holes in the communication network and reach out to immediately relevant experts before tasks fall behind schedule and be intentional in activating sub-teams in tiers 2 and 3 within their role to prepare for upcoming issues.

5. Boundary Spanning for External Connectivity: Team members should stay adaptive in their communication exchanges with others regardless of their tiers and role. To ensure external connectivity, project leads should encourage an environment of collaboration and trust to promote boundary-spanning knowledge transfers. One of the interviewees reported on boundary-spanning ties:

> *"… I don't have to have all communication and to be in the middle of it. I can delegate some of that. When I have those conversations with the mechanical engineers within our organization, they can reach out to the designer and communicate together and come back with a result, and then I can give directions to the general contractor."*

Similarly, team members should not depend on tier 1 members to facilitate and/or initiate information exchanges when the relevant project issues are present by keeping managers in the loop. One lead from the general contractor reported on boundary-spanning ties:

> *"...Whatever you cross the line (from 2- tier3), the primary folks are aware of those conversations. We asked to be copied in these conversations. If we are not a part of the conversation, we asked to be summarized and published. We agree that from a process standpoint it might be necessary, but we need the summary of the conversation."*

Post-intervention feedback proved that the observations and findings of the study reflected the project delivery processes and communication strings of the team. The team members commented that the sociograms and intervention strategies gave insight into how team members communicated during the project delivery and how it should be used in future projects. They also highlighted the need that the findings should be shared with senior leadership in the organizations to create awareness of organizational assignments, team member selections based on qualifications, skill development, and project management.

4.7 Discussion

Consisting of a wide range of experts, organizations, and stakeholders, AEC project teams are complex and prone to impairment. Enabling successful knowledge transfers and collaboration among team members is of utmost importance to successfully deliver a project. This study analyzes an AEC project network systematically and thoroughly to shed light on how team collaboration might be improved through informed network interventions.

First, the project teams might benefit from having a team of two for each role (i.e., owner, designer, and general contractor) consisting of a "technical lead" making decisions and a "communication lead" facilitating key information exchange among relevant experts. Communication of client requirements clearly and diffusion of technical knowledge is necessary for successful project execution (Cross et al. 2008). Therefore, managers should consider involving team leaders early in project delivery (Franz et al. 2017), especially in high-profile projects, where the project needs, and expectations are higher. Having two leaders might improve resiliency during personnel and phase transitions and avoid bottlenecks (Cross et al. 2006). Findings also indicate that trust is an important prerequisite for effective knowledge transfers and therefore, project performance (Cheung et al. 2013; Chinowsky et al. 2008). The prior working experience was observed to reinforce trust and effective knowledge transfers between team members, as teams with prior experience can resolve conflicts and adapt to contingencies easier instead of depending on contractual relationships (Girmscheid and Brockmann 2010; Lee and Chong 2021). Therefore, managers should consider bringing people with previous experience on board, especially in key roles such as technical and communication leads and support. Interview results supported our finding:

> *"I think this is a high-functioning team because we have worked on projects before. There are a few [new team members]. We can effectively communicate and there is an added level of trust going through the other projects."*

Second, it is recommended to have "communication support" in tier 2 as a broker to assist "communication lead" in tier 1. Therefore, responsible parties should ensure timely involvement of communication supports and empower them, as they help disseminate project information upwards and downwards in tiers and across different roles (Liu et al. 2022). Involvement of communication supports also strengthens the triadic closures (i.e., complete ties among three actors) across tiers and roles. Even though triads might seem redundant, they might strengthen trust (Henry and Vollan 2014), facilitate cooperative behaviors, and improve resiliency for staff turnovers (Franz et al. 2018).

Third, results are in parallel with the literature and suggest that project leads, and brokers should effectively engage with peripheral members by inviting them to face-to-face meetings (Cross et al. 2006) for targeted discussions for a limited and planned time to protect them from communication overload, which involves them in problem-solving better Zhao et al. (2021) and improve their sensitivity towards project priorities (Cross et al. 2008). Similarly, by bridging the fragmentation points with the rest of the network with the involvement of the communication lead and support, the transmission of new ideas and knowledge transfers can be promoted (Kadushin 2012).

Lastly, team members should stay adaptive in their communication exchanges with others regardless of their tiers and role by crossing the boundaries of role, tier, and expertise. In parallel with the literature, having boundary spanners facilitated effective knowledge transfers with external stakeholders and helped improve project performance (Duva et al. 2020; Marco et al. 2010; Ramalingam and Mahalingam 2011). The management team should empower relevant experts to get engaged by spanning the boundaries of their role, tier, or expertise by keeping the management in the loop.

4.8 Conclusion

Network interventions can help improve project efficiency and performance by enabling necessary practices and desired behaviors, and generating social influence (Valente 2012), and yet there is a lack of robust intervention protocols that can be repeated for AEC project networks (Matous et al. 2021). This study contributes to the body of knowledge by using social network analysis in pursuit of developing an intervention protocol to improve the efficiency and performance of project communication networks.

The results provide intervention implications in relation to organizational assignments, communication and coordination practices, and skill development that project executives and personnel can use for timely improvements in the AEC project delivery. First, project organizations should have technical, and communication leads in tier 1 of each role (i.e., owner, designer, and general contractor) to balance workload, improve system resilience, and ensure the necessary knowledge transfers. Second, communication support in tier 2 as an information broker can be highly essential in designer and general contractor roles to assist project communication coordination. Third, peripheral members and fragmentation points should be bridged with the rest of the network to promote the diffusion of novel information by using communication support and by inviting them to face-to-face meetings for a limited capacity. Fourth, the management team should ensure that relevant experts are engaged by spanning the boundaries of their role, tier, or expertise by keeping the management in the loop.

Limitations exist in this study that should be considered and addressed in future research. First, this research used Cross et al. (2006)'s protocol to develop strategies for AEC teams by using data from a single, medium-size case study, which might limit the generalizability of the findings. In addition, although the literature and our participant verifications provide validity to our methods, we acknowledge that each project is unique and parameters such as contract types, communication protocols, and characteristics of team members might impact the findings and team performance.

Therefore, future research should use data from bigger or smaller projects with different individuals to test and validate the applicability of the intervention strategies. Specifically, future research can explore personality characteristics for team members that enhance system functioning and resilience. Future research also can focus on automating the development of social network-based evaluation of project teams by using technology to provide real-time feedback during project delivery, continuously improve participants skills and enable individual learning. Nevertheless, this study provides a foundation for future work including but not limited to, application in other industries for project team interventions across disciplines and organizations.

4.9 Acknowledgements

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5 OVERVIEW OF THE RESEARCH

5.1 Summary of Research

AEC project teams are complex and made up of a diverse group of individuals who work on a project on a temporary basis for a specific time. Therefore, fragmentation problems are common, and experts often fail to collaborate efficiently and benefit from each other's expertise. To overcome the challenges of complexity, the AEC industry seeks remedies to achieve team integration.

The SNA approach allows evaluation of team integration, communication, and knowledge sharing and helps find corrective actions for problems encountered in project networks. However, construction teams are dynamic and organizational structure is not enough to understand project collaboration networks. Thus, a longitudinal and multi-level analysis of network topology is necessary to understand which network characteristics are favorable for AEC project outcomes, especially for sustainability, how project networks evolve during project delivery, how network actors influence each other in the pursuit of collaboration and knowledge sharing, and how collaboration networks can be leveraged to better enable expertise flows.

To address the gap in the literature, the overall goal of this research is to develop a holistic understanding of project social networks that allow actors to generate and channel knowledge that can be used to optimize outcomes including sustainability for AEC projects. The objectives accomplished to achieve this goal include:

1. Evaluation of the emergence and evolution of the case study project's network and identification of the network characteristics that allow experts to exchange knowledge to optimize sustainability outcomes for AEC projects.

2. Examination of the social influence mechanisms in project networks to understand the changes in knowledge transfer behaviors for sustainability and developing a quantitative model to understand how project-level knowledge transfer, including all team members from all groups, influences group-level knowledge transfer in complex project collaborations
3. Systematic review of performance and communication trends of the collaboration networks of a project and development of an intervention framework that can potentially increase expertise flows and system resilience and help improve project outcomes.

The chapters in this dissertation where the objectives above were achieved, and the methods employed include:

1. Objective 1 accomplished in Chapter 2: Reviewed SNA literature in AEC, complex project teams and sustainability domains to identify the network metrics and topology features that might impact the sustainability outcomes and conducted SNA longitudinally to elucidate the desirable network characteristics.
2. Objective 2 accomplished in Chapter 3: Based on the Social Influence Theory, developed a social influence model and performed a linear regression to test how individuals change knowledge transfer behaviors, particularly how network-level knowledge transfer impacts the sub-team level knowledge transfer behaviors.
3. Objective 3 accomplished in Chapter 4: Collected longitudinal data and evaluated performance and communication trends of the case study project's collaboration network to develop an intervention framework for AEC teams to increase expertise flows, improve system resilience and improve project outcomes.

5.2 Summary of Findings

The study's main contribution to the body of knowledge is the holistic assessment of project networks that allow actors to generate and channel knowledge that can be used to optimize outcomes including sustainability for AEC projects in the light of progress loops. The study's key findings and their practical applications for AEC project teams are compiled in Table 5-1.

Table 5-1. Summary of findings and practical applications

Chapter 1	
Findings	*1. In contrast to the literature, no evidence of a relationship between network metrics and sustainability performance was detected except for the betweenness centrality.* *2. Increased network exposure and boundary-spanning ties in networks can have a positive impact on sustainability performance.* *3. Involvement of team members with diverse expertise areas in collaboration networks and project meetings might have a positive impact on performance, especially during the design phase.* *4. Even though increased network exposure might have a positive impact of performance, it can be detrimental after a certain threshold, especially at times of disruption* Practical Applications: Project management should determine the boundaries of the sustainability networks carefully by identifying the parties that ideally should collaborate and ensure expertise diversity. Based on the LEED guidelines (USGBC 2020) team members who should ideally collaborate for optimized EA outcomes are commissioning authority, owner, mechanical engineers, building manager, lighting designer, contractor, and occupants. Based on this research, building maintenance parties and capital project delivery members should be involved in project collaboration when necessary. To avoid information overload, targeted involvement of the experts should be enabled by creating communication protocols for email exchanges and arranging meeting attendance intentionally. The management team should also consider the needs of different phases, as design and construction phases showed different needs pertaining to the number of experts and expertise diversity in the networks and during team meetings. During the design phase, inviting necessary parties to team meetings might be beneficial for goal alignment and coordination. In a sample scenario, when the architectural designer plans spaces of a building, it is important to have the mechanical designer cooperate with them to select HVAC systems according to the space and energy efficiency needs, and general contractor provide information for constructability input.

Table 5-1 (cont'd)

Chapter 2	
Findings	*1. Individuals with a higher influence and central position in the networks spread their attitudes to the people they interact with*. *2. Knowledge transfer behavior is dynamic and team members tend to share knowledge more in the networks as a result of being exposed to the knowledge of others.* *3. Exposure to diverse information from different social circles and expertise areas within the project is a significant predictor of the subsequent knowledge transfer within the sustainability sub-team.* *4. Even though opinion leaders are good at influencing and changing the behaviors of others, they are reluctant to change their behaviors*. *5. Eigenvector centrality can be used as a proxy for knowledge transfer behaviors*. Practical Applications: Team members adopt different behavior patterns from their colleagues in projects. Therefore, project managers should involve key parties in project delivery early in the design phase to enable goal alignment, as it is highly important for sustainable AEC projects. Project managers should promote interactions between opinion leaders and especially peripheral members to spread knowledge sharing behaviors of opinion leaders to all project members to achieve higher integration. Spreading desirable knowledge transfer practices to others might increase cohesion and performance.

Table 5-1 (cont'd)

Chapter 3	
Findings	*1. Project teams might benefit from having a team of two for each role (i.e., owner, designer, and general contractor) consisting of a "technical lead" making decisions and a "communication lead" facilitating key information exchange.* *2. "Communication support" in tier 2 as a broker to assist communication lead in tier 1 can positively impact project networks in reducing communication overload for tier 1 members and connectivity of the larger project team networks* *3. Project leads and communication support should effectively engage with peripheral members by inviting them to project meetings for targeted discussions and bridge the fragmentation points with the rest of the network to promote transmission of new ideas.* *4. Team members should stay adaptive (and be empowered and encouraged to do so) in their communication exchanges with others regardless of their tiers and role by crossing the boundaries of role, tier, and expertise.* Practical Applications: Organizations should consider selecting technical and communication leads based on the qualifications, such as prior working experience together and their experience levels and involve them early in project delivery to ensure the communication of client requirements and diffusion of necessary technical knowledge. Project managers should empower the communication lead to find the gaps in the networks and connect the fragmented network cliques. Especially, communication support in designer starting with design phase and in general contractor starting with construction phase is crucial as those roles lead project communication. As previously mentioned, the network cliques relying heavily on email communication should be detected and invited to project meetings by the management team. The management team should empower relevant experts to get engaged with their peers by spanning the boundaries of their role, tier, or expertise while keeping the management in the loop based.

5.3 Deliverables

The primary deliverable of this research is the holistic assessment of project social networks that allow actors to generate and channel knowledge that can be used to optimize outcomes including sustainability for AEC projects. This output draws on key findings which are described in detail in chapters 2, 3, and 4, and summarized in Table 5-1 In addition, this deliverable is accompanied by the following ones:

1. Review of relevant SNA literature in AEC, complex project teams, and sustainability domains and theoretical discussion on the influence of network metrics and topology features on sustainability outcomes during the design and construction phases of project delivery.
2. Development of an influence model to quantitatively describe the changes in knowledge transfer behaviors, especially relating to sustainability, occurring as a result of interactions and practical applications for project management team.
3. Review of the relevant intervention literature and development of an intervention framework for AEC teams and providing practical implications for practitioners.
4. Theoretical and methodological implications of social networks in inter-organizational and inter-disciplinary project teams.
5. Practical applications of social networks for different organizations and roles in the AEC industry to improve project outcomes.

5.4 Intellectual Merit

Collecting network data on large settings such as AEC project teams is an arduous task unless the interaction between individuals leaves a record, such as email exchanges (Kadushin 2012). Most SNA studies in the AEC domain used survey data to analyze project networks and create sociograms. However, surveys might give an idea about the egocentric networks of the respondents and cannot provide a larger picture of the project network. Moreover, most previous studies were cross-sectional in nature. Unlike the previous studies, this research collected email data longitudinally in a joint effort with the project's main organizations and examined the AEC project networks using project episodes as the key time points of reference. The data set used consisted of more than 21,000 emails and 1,000 individuals after the irrelevant data was eliminated. Working on such big data gave greater insights into project collaboration networks.

This research developed an understanding of what happens, why things happen, and how things happen in a network at individual, sub-team, and project network levels. After identifying the network features and understanding the background drivers forming them, this study provided an intervention framework to find remedies for better performance.

5.5 Broader Impacts

The findings of this study will have implications for interdisciplinary and inter-organizational project team settings outside of the AEC domain. Especially, the intervention framework prepared in the light of the performance and communication metrics has a strong potential to be applied in complex project teams.

5.6 Limitations

Limitations exist in the study, which can be addressed in future research. The scope and generalizability of the findings might be limited due to the use of a single, medium-size case study. We acknowledge that each project is unique and parameters such as contract types, communication protocols, and characteristics of team members might impact the findings and team performance. Future research can use data from smaller or larger projects implementing different PDMs. In addition, although the literature and our participant verifications provide validity to our methods, SNA was conducted without examining the impact of different communication methods such as face-to-face interactions, online meetings, or text messages. Nevertheless, this study provides a foundation for future work and sheds light on AEC project team networks.

5.7 Future Research

Future research should refine the findings of this study using different projects with different characteristics. The network metrics studied herein should be investigated in different project settings with additional considerations including but not limited to team members' personality traits, owner's management, and leadership culture. Second, even though we identified the influence mechanisms and a causal relationship between project-level and sustainability group-level knowledge transfer, future research should investigate possible confounders for our causal estimates. Lastly, future research also can focus on automating the development of social network-based evaluation of project teams and interventions by using technology to provide real-time feedback during project delivery, continuously improve participants' skills and enable individual learning.

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APPENDIX A: Data Collection Protocol

Protocol Description

This study proposes a research design that includes a treatment project (Group A) and a control project (Group B). These projects will be from the Architecture, Engineering and Construction (AEC) industry. The individuals working in these project teams will be invited to participate in the study as summarized below.

Groups A & B:

1. Individuals in both AEC projects will be asked for consent and give permission to the research team to do the following during the AEC projects:
    - Collect e-mail exchange data via the Owner's IT Department (exchange data is limited to subject, sender, recipient(s), and date/time),
    - Attend, observe and record their project team meetings,
    - Access and observe the project's web-based document sharing platform and artifacts such as LEED checklists on a need basis.
2. All team members will be asked to fill out a short demographics survey at the beginning of the study.
3. Two to four times during the AEC projects:
    - All individuals will be asked to fill out a groups' assessment surveys.
    - Select leaders will be asked to fill out individuals' assessment surveys.
    - Select owner, designer, contractor, and subcontractor representatives will be asked to attend interviews.
4. As mentioned in Task 3 below, there are some individuals, who are working as a vendor, subcontractor etc. for our consented study participants but they do not come to the project

meetings. Therefore, we cannot get their consent. However, those people are copied in the project e-mails, and we capture their e-mail data while we are getting e-mail exchange data of our consented individuals. Since this e-mail exchange data is shared with us by the primary consented participants and not considered as human subject data, we do not need their consent (Approved by MSU IRB). In order to expand the boundaries of our research, these secondary participants, who were captured in the e-mails will be asked to fill out the two online surveys as indicated below without being involved in any other steps of the study. Therefore, a new and partial consent form is created for those individuals (Please see the Survey Consent)

- Secondary individuals will be asked to fill out a groups' assessment survey.
- Selected individuals will be asked to fill out individuals' assessment surveys.

Group A- Treatment Group: In addition to the above data collection efforts, only the individuals in the treatment project (Group A) will be asked to attend network intervention sessions.

Project steps are explained in detail below.

Recruitment Process:

1. We will collect data from those teams in the next 3 years. The owner was already contacted before proposal submission. Right after the award notification we contacted the owner again to discuss the availability of projects.
2. Once the owner identifies the projects to collect data on, we will ask each project's owner's representative to introduce us to project managers working for other key parties in the projects such as general contractor, designer, subcontractors, and suppliers (See E-mail #1 and Recruitment Flyer).

3. We will meet the project managers in all key parties in person or via zoom and present the project goals and processes. The Research Project Information Forms in the attached (separate forms for the control and treatment projects) will help guide this meeting. We will learn about the email management practices for specific organizations during this meeting (whether they are stored centrally in addition to individual storage or not).

Task 1: Upon receiving the project managers' permission, the researchers will attend the first project team meeting in each project to make a presentation on the objectives and procedures of the study to all project team members and will use the recruitment flyer in the attached. The researchers will distribute the consent forms (See Informed Consent Form #1A for the Treatment Project and #1B for the Control Project) to the meeting attendees requesting their participation. After the consent forms are signed and returned, a short Demographics Survey (asking their information on gender, age, and race, occupation, educational level, experience in the industry - see in the attached) will be handed out and participants will be asked to fill it out at this time.

If the attendance is low in the first meeting, the researchers will attend the second project team meeting. If there are people that research team cannot connect at the first or second project team meetings, or there are people joining the team later, these people will be invited for a Zoom video conference or in person meeting. The research team will present the research project, invite them to participate and give them the consent form individually.

Task 2: After getting the consents of all the team members, the owner's project managers will be asked to provide us the roster (names and email addresses of the individuals in these projects on their own team) and add our credentials for access to the web-based document haring platform (See E-mail #2).

Task 3: After getting the Informed Consent signed by the team members, the owner's IT department will be contacted via email requesting the email headers for the consenting individuals (See E-mail #3). The IT department will provide us the e-mail exchange information within the treatment and control projects. This information will include the following: 1- The sender of an email in the roster 2- The recipient of an email in the roster 3- The subject line of the email 4- The date and time it was sent. Upon receiving the data, we will scan the sender and receiver information on the email headers to see if any non-consenting and or outside of team roster individuals' email addresses are captured in the email headers. If so, we will assign those dummy codes concealing their identities but showing their areas of expertise since these are individuals' e-mail addresses that are not our study participants', and this data is considered secondary data for our study that would help us identify the frequency and type of expertise that flow through the network through our study participants. These individuals work as subcontractors, vendors etc. with our study participants on the case study projects we are collecting data from and are copied in email case study project e-mail correspondence. This secondary data is considered as case study project information and not necessarily human subject data as it belongs to participating organizations. The primary study participants from the participating organizations give consent to share this data with the study team per our protocol. The IT Department will provide the information above weekly or bi-weekly during the whole project delivery for both treatment and control projects. The owner's IT department will provide us with the owner organization's emails. To capture all key project emails, we will work with the contractor and the designer's project managers and their IT departments in a similar manner.

Task 4: Based on the collected data, the researchers will identify the key team members in the project networks and ask them to verify findings in person, give feedback on the network findings, and take Survey #2 via e-mail (See E-mail #4). These select leaders from both project teams will evaluate the individual performance of team members within their sub-group. Before sending out Survey #2, we will run a pilot survey with randomly selected members to improve the survey questions/items.

Task 5: After the sub-group leaders confirm the sociograms in the previous task, the individuals under each sub-group will be requested to complete Survey #3 via e-mail (See E-mail #5). To improve the response rate, prior to sending the emails, the researchers will make an announcement in the project team meetings that an online survey will be sent shortly via e-mail to team members. Before sending out Survey 3, we will run a pilot survey with some members randomly selected to improve the survey questions/items.

Task 6: Research team will conduct structured interviews with owner, designer, contractor, and key subcontractor and supplier representatives (Please see Interview). We will hold zoom or phone interviews with the interviewees individually or in groups of two as outlined in the attached interview script.

Task 7: Tasks 3-6 in the treatment projects and Tasks 3-8 in the control projects will be repeated periodically for 1 to 4 times across the project delivery timeline.

Task 8: The researchers will implement a network intervention in the treatment group based on interview outcomes and the data analyzed (Please see the intervention script attached). The intervention sessions will be on Zoom or in person, and individually or in teams of two.

Protocol Addenda:

I. Research Flyer

Figure A-1. Research flyer

II. Email #1

Email Subject: MSU Research Project – Network Interventions

To: Project's Owner's Representative

Dear *"team member":*

As a follow up to X's e-mail, I'd like to take this opportunity to introduce myself and our project. I am an Associate Professor at MSU's Construction Management Program. My team and I will be conducting research regarding social networks in inter-organizational AEC (Architecture, Engineering, and Construction) projects.

The goal of this project is to advance our understanding about how optimizing interactions across disciplinary boundaries in inter-organizational AEC Project teams can improve sustainable outcomes. Please see the attached flyer for details.

To achieve this project goal, we will need to collect data from all team members on the *"project name"* project and are in need of your support. As a part of this effort:

1. Can we set up a meeting with you (in person or via zoom) at your earliest convenience to tell you about the project scope?
2. Can you please introduce me to the other project managers in the team that are working for the other key parties in the projects such as general contractor, designer, key subcontractors, and key suppliers so we can initiate this conversation with them as well? I understand that if you would like to wait until after our face-to-face meeting to facilitate this e-introduction.

Thank you very much for your time in advance.

Best regards,

Sinem Mollaoglu-Scott, PhD, LEED AP, CGP

III. Email #2

Email Subject: MSU Research Project – Requesting the *"project name"* Project Team Roster

To: Project's Owner's Representative

Dear *"team member":*

As a part of our research protocol, we would like to request the project team roster (listing all individuals' names, organizations, and e-mail addresses) of the *"project name"* project from you.

Can you please also add the doctoral student to our research team, Meltem Duva (duvamelt@msu.edu) for access to the web-based document sharing platform?

Thank you for your help in advance.

Best regards,

Sinem Mollaoglu-Scott, PhD, LEED AP, CGP

IV. Email #3

Email Subject: MSU Research Project – E-Mail Headers of the Project *"project name"*

To: Project's Owner's IT Department

Hello *"IT member":*

I am Meltem Duva, a PhD student of the Construction Management Program at Michigan State University. I am conducting research with Dr. Sinem Mollaoglu and Dr. Dong Zhao regarding social network interventions in inter-organizational Architecture, Engineering, and Construction projects.

"As discussed earlier, we are requesting the e-mail exchange information for the *"project name"* projects for our research that are limited to email headers (only to, from, subject and date/time fields). Attached are the project team member email addresses (rosters) we need the email headers for. Please note the following when pulling out this data: TO and FROM lines in the email header should both include email addresses that are listed in the attached rosters, so we are limiting the data collection to those related to only project specific information. Upon receiving the data, we will scan the sender and receiver information on the email headers to cross out the non-consenting or irrelevant individuals that might be captured in the email headers.

Please see our IRB Approval letter in the attached.

Thank you for your cooperation!

Best regards,

Meltem Duva

PhD Student and Graduate Research Assistant

V. Email #4

Email Subject: MSU Research Project – Web-Based Survey for Project Leaders - Please Complete by Date "X"

To: Sub-Group Leaders

Hello *"team member":*

As a follow up to our meeting on *"date",* we are sending you the survey link below to evaluate the individual performances of your team members to date on the *"project name"* Project. Based on our meeting, the individuals listed below have been working closely with you recently. Please fill the survey out for these individuals:

- *name*
- *name*
- *name*
- *name*

Please complete it within two days by Date X at 9 pm. Completing the survey/s will take around 5-15 minutes.

https://www.linktothesurvey#1.com

Thank you for your cooperation!

Best regards,

Meltem Duva

PhD Student and Graduate Research Assistant

VI. Email #5

Email Subject: MSU Research Project – Online Survey for Sub-group Evaluations-Please Complete by Date "X"

To: All Team Members of the Projects

Dear "team member "of project "project name"

As a follow up to our announcement at the Project Team Meeting on *"date",* please find the link below to evaluate your sub-group sustainability performance in the last 3 months.

Our study shows that you have worked in the following sub-groups during this time. Please fill out the survey for each of these sub-groups:

- *name*
- *name*
- *name*
- *name*

Please complete it within two days by Date X at 9pm. Completing the survey/s will take around 5-15 minutes.

https://www.linktothesurvey#1.com

Thank you for your time in advance.

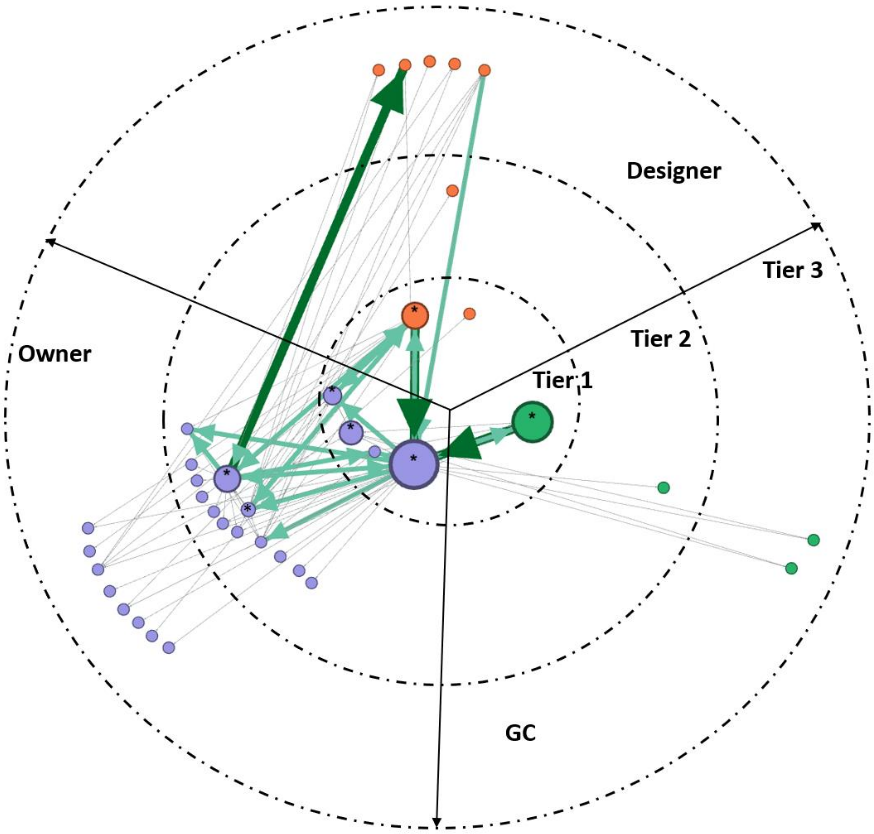
Best regards,

Meltem Duva

PhD Student and Graduate Research Assistant

VII. Interviews with *"project name"* Project Team Members

Interview with the Owner's Representative in the Core Team:



Legend:

- Tier 1 includes the main representatives from each side (Owner, designer, or GC)
- Tier 2 represents team members from Tier 1 members' home organizations.
- Tier 3 represents all other individuals working on the project including subcontractors, trades, consultants, and other stakeholders.

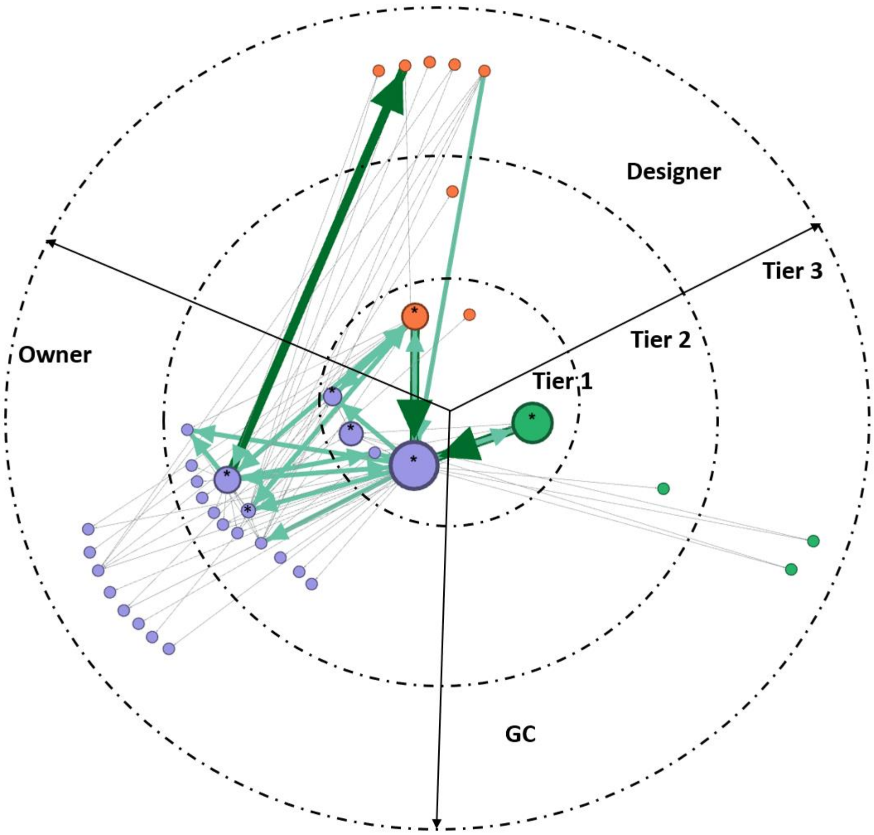
Figure A-2. Sociogram showing organizational structure

1. How do you coordinate with Tier 2 and 3 and other parties' Tiers 2 and 3?
   - What happens when coordination does not go well?
   - What do you do? Who do you talk to?

2. We did a survey for the performance of the individuals for this project's schematic design phase. We found out that the highest and lowest performers in this project were closely tied to you in email communication network.
   - One of the high performers is from *"owner department name"* and the other is from designer.
   - Low performers are from *"owner department name"*.
3. We note that you communicate with several of these people. Can you tell us how that came about? Follow up questions:
   - What are the intents of these information exchanges (technical, coordination etc.)?
   - What are the other factors that may have brought you with them?
   - It seems to us that you are taking the role of coordinating information among these people. Are you intentionally compensating for information gaps in this network due to those low performers? If so, how?
4. In our analysis of email communication network, we saw that most members in the core project team have a support member who has a similar expertise. However, some low performers, that are also in the core project team, do not have such a support. Can you tell us why that might be, and what might be the implications? Follow up questions:
   - Do you think lack of such a supporting member in the team (with similar areas of primary expertise in the project team) can lead to low performance for individuals?
   - If so, do you agree it can be necessary to involve another member with similar expertise to support core member functions?
   - Can you think of examples in your project network?

5. Have you assigned someone to help you out with the massive information flow in this project (both technical and coordination related)? If so, at what stage of the project? If not, would you want to do that? What has been the peak time for the information flow in different phases of the project.
6. Has there been a stage in this project where you felt like you carried more than one heavy role? (For example: Coordination for information flow and technical expertise in *"company name")*
7. When considering high visibility projects like *"project name"* where there are high number of stakeholders involved, is it worth considering the assignment of an additional expert at Tier 1 to help facilitate technical and coordination lead duties?

Interview with two Designer Representatives in the Core Team:



Legend:

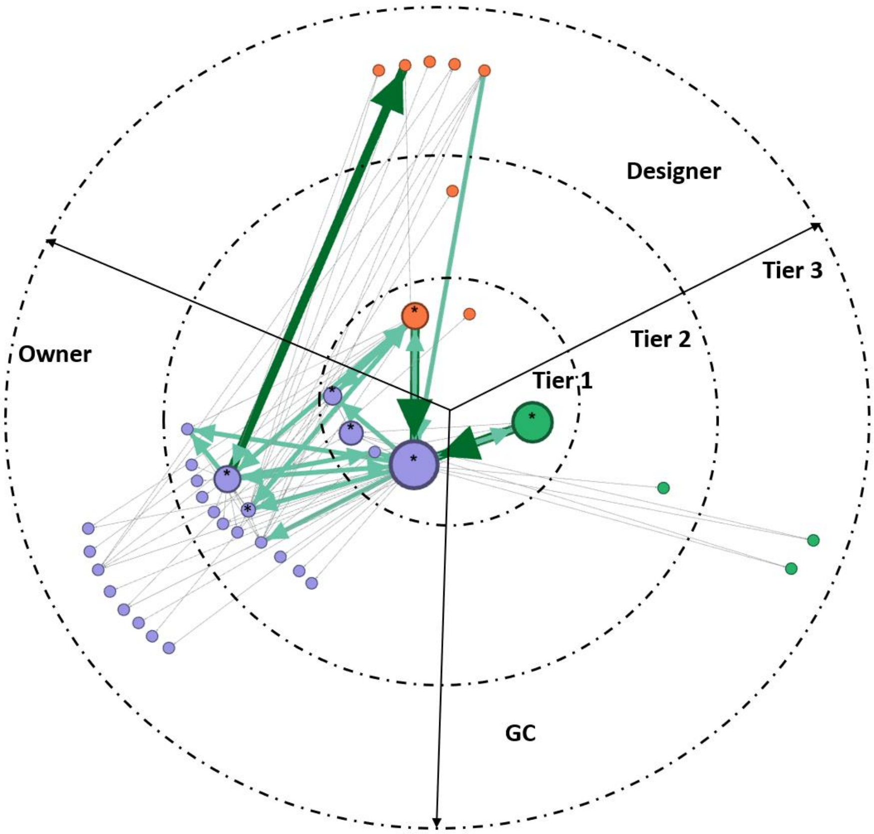
- Tier 1 includes the main representatives from each side (Owner, designer, or GC)
- Tier 2 represents team members from Tier 1 members' home organizations.
- Tier 3 represents all other individuals working on the project including subcontractors, trades, consultants, and other stakeholders.

Figure A-3. Sociogram showing organizational structure

1. How do you coordinate with Tier 2 and 3 and other parties' Tiers 2 and 3?
    - What happens when coordination does not go well?
    - What do you do? Who do you talk to?

2. We see that some individuals from the designer side frequently communicate with other members in owner or contractor side with the same expertise area. For example: Orange colored circles connecting across tier 2 of owner and tier 3 of designer side.
    - Are you aware of this type of communication?
    - If so, do you intentionally facilitate this communication?
3. One of our observations is that in the core design team (attending project team meetings), you have two dominant experts that have been constant in all design phases who (a) facilitate technical expertise and (b) heavily collect and disseminate information for getting tasks done across project team members.
    - Is that a strategy you follow or has that evolved organically?
    - Do you find it to be useful for team and project performance?
4. Another one of our observations is that, until design development, you had an experienced team member that coordinated communications for ALL project team members (including contractor and owner). After the design development stage, this person phased out of the project team and a tier 2 individual at your organization emerged as an active node in the communication network bridging outside organizations to designer core team and also contributing to the communication network with links to contractor and owner parties.
    - Is this an intentionally assigned role to this person or has it organically emerged?
    - In any case, what do you think of the impacts on the team and project performance of these two different (in terms of power and seniority in the project team) individuals?

Interview with *"owner department"* Representative in the Core Team:



Legend:

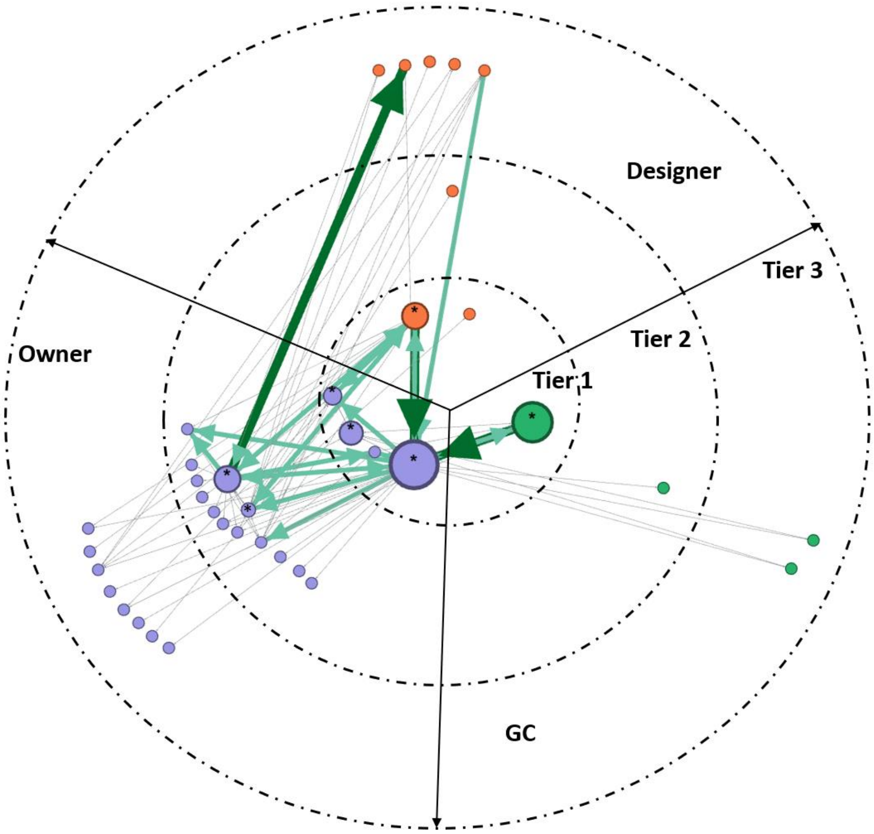
- Tier 1 includes the main representatives from each side (Owner, designer, or GC)
- Tier 2 represents team members from Tier 1 members' home organizations.
- Tier 3 represents all other individuals working on the project including subcontractors, trades, consultants, and other stakeholders.

Figure A-4. Sociogram showing organizational structure

1. How do you coordinate with Tier 2 and 3 and other parties' Tiers 2 and 3?
   - What happens when coordination does not go well?
   - What do you do? Who do you talk to?

2. We observe someone in the core has the same expertise as you. Can you explain how that works out?

Interview with two Contractor Representatives in the Core Team:



Legend:

- Tier 1 includes the main representatives from each side (Owner, designer, or GC)
- Tier 2 represents team members from Tier 1 members' home organizations.
- Tier 3 represents all other individuals working on the project including subcontractors, trades, consultants, and other stakeholders.

Figure A-5. Sociogram showing organizational structure

1. How do you coordinate with Tier 2 and 3 and other parties' Tiers 2 and 3?
   - What happens when coordination does not go well?
   - What do you do? Who do you talk to?

2. We see that some individuals from the designer side frequently communicate with other members in owner or contractor side with the same expertise area. For example: Orange colored circles connecting across tier 2 of owner and tier 3 of designer side.
    - Are you aware of this type of communication?
    - If so, do you intentionally facilitate this communication?

VIII. Surveys for Data Collection

Demographics Survey

Survey 1: Engineering Project Networks – Demographics Survey

Q1: Your name and your title in the project:

Q2: Your gender:

- ○ Male
- ○ Female
- ○ Other

Q3: Your race (You can select more than one option):

- ☐ American Indian or Alaska Native
- ☐ Asian
- ☐ Black or African American
- ☐ Hispanic or Latino
- ☐ Native Hawaiian or Pacific Islander
- ☐ White
- ☐ Other

Q4: What is the primary role that you represent in this project?

Owner

- ○ Administration
- ○ Planning, Design and Construction
- ○ Power and Water
- ○ Sustainability
- ○ Other ________________

Design

- ○ Architect
- ○ Interior Designer
- ○ Landscape Architect
- ○ Other ________________

Engineering

- ○ Structural Engineer
- ○ Civil Engineer
- ○ Mechanical Engineer
- ○ Electrical Engineer
- ○ Other ________________

○ General Contractor

Subcontractor

- ○ Mechanical
- ○ Electrical
- ○ Plumbing
- ○ Other ________________

Supplier

- ○ Concrete
- ○ Steel
- ○ Other

○ Other ________________

Q5: How many years have you been working full time in architectural, engineering and construction industry?

- ○ 1-2 years
- ○ 2-5 years
- ○ 5-10 years
- ○ 10-15 years
- ○ More than 15 years

Q6: What is your education level?

- ○ Less than high school
- ○ High school diploma or equivalent
- ○ Some college, no degree
- ○ Postsecondary non-degree award
- ○ Associate degree
- ○ Bachelor's degree
- ○ Master's degree
- ○ Doctoral or professional degree

Q7: Considering the *"project name"* project, how many similar projects have you worked on prior to this project?

- ○ 1-2
- ○ 2-5
- ○ 5-10
- ○ More than 10

Q8: Excluding this project, how many LEED or other certified sustainable projects have you worked on?

- ○ 1-2
- ○ 2-5
- ○ 5-10
- ○ More than 10

NOTES: Please answer these questions considering *"project name"* project.

Evaluation Survey

Research Survey of *"project name"* Project

MSU Construction Management Program
School of Planning, Design, and Construction

The survey contains a series of questions regarding your team members' performance in the *"project name"* project. Please respond based on your perceptions.

The survey will take around 10 minutes. It will work best in a laptop/computer rather than in a mobile device.

By starting the survey, you agree to participate.

Your name and title in the project:

1. List the area(s) of expertise you bring to this project starting with the most relevant, and

2. Evaluate your level of experience for each area.

Example Expertise Areas: Architectural Design, Mechanical Construction, Electrical Engineering, Project Needs and Program.

	Very Low	Low	High	Very High
Expertise Area 1	○	○	○	○
Expertise Area 2	○	○	○	○
Expertise Area 3	○	○	○	○
Expertise Area 4	○	○	○	○
Expertise Area 5	○	○	○	○

In this survey, you will respond a series of questions relating to:

1- Your subgroup, which consist of the people you work closely,
2- Your subgroup leader(s), which were determined based on email frequency,
3- Randomly selected 5 people from your subgroup.

1- Generic Survey Questions

Respond the questions below knowing that: **1 = strongly disagree; 2 = disagree; 3 = agree; 4 = strongly agree and N/A= not applicable**.

During the LAST THREE MONTHS, "your subgroup", or "subgroup leaders" or "individuals" successfully:

	"name"				
	1	2	3	4	N/A
1. Completed tasks with the expected quality	○	○	○	○	○
2. Completed tasks on time	○	○	○	○	○
3. Completed tasks within budget constraints	○	○	○	○	○
4. Completed tasks within MSU's sustainability standards	○	○	○	○	○
5. Completed tasks to achieve the overall project goals	○	○	○	○	○
6. Collaborated efficiently with team members from other disciplines to achieve the project goals	○	○	○	○	○
7. Provided information needed to accomplish tasks	○	○	○	○	○
8. Communicated effectively with the team members	○	○	○	○	○
9. Adapted well to changes in the project to complete tasks	○	○	○	○	○
10. Contributed to create alternative solutions to adapt to project changes	○	○	○	○	○
11. Understood well how to deal with changes in the project to achieve the project goals	○	○	○	○	○
12. Resolved conflicts if they arose	○	○	○	○	○
13. Contributed with new improved ways to develop tasks when the project goals were not met	○	○	○	○	○
14. Created innovative solutions to improve the project quality	○	○	○	○	○
15. Developed alternative solutions to achieve the project goals ahead of time	○	○	○	○	○
16. Contributed to create alternative budget-conscious solutions to achieve the project goals	○	○	○	○	○
17. Developed alternative solutions to achieve the project goals within the sustainability requirements	○	○	○	○	○
18. Developed new solutions to overcome issues hindering the project goals	○	○	○	○	○
19. Designed new collaboration methods to achieve project goals	○	○	○	○	○

APPENDIX B: Institutional Review Board Approval Letter

MICHIGAN STATE
UNIVERSITY

Modification and Continuing Review APPROVAL
Pre-2018 Common Rule

June 9, 2022

To: Sinem Mollaoglu

Re: **MSU Study ID:** STUDY00001064
IRB: Social Science / Behavioral / Education Institutional Review Board
Principal Investigator: Sinem Mollaoglu
Category: Expedited 7
Submission: Modification and Continuing Review MODCR00001135
Submission Approval Date: 6/9/2022
Effective Date: 6/9/2022
Study Expiration Date: 6/8/2023

Title: Understanding Impacts of Social Network Interventions on Engineering Project Outcomes
Proposal Number: 32578

Office of Regulatory Affairs
Human Research Protection Program

4000 Collins Road
Suite 136
Lansing, MI 48910

517-355-2180
Fax: 517-432-4503
Email: irb@msu.edu
www.hrpp.msu.edu

This submission has been approved by the Michigan State University (MSU) SIRB. The submission was reviewed by the Institutional Review Board (IRB) through the Non-Committee Review procedure. The IRB has found that this study protects the rights and welfare of human subjects and meets the requirements of MSU's Federal Wide Assurance (FWA00004556) and the federal regulations for the protection of human subjects in research (e.g., pre-2018 45 CFR 46, 28 CFR 46, 21 CFR 50, 56, other applicable regulations).

This letter notes approval of changes to study team personnel.

How to Access Final Documents
To access the study's final materials, including those approved by the IRB such as consent forms, recruitment materials, and the approved protocol, if applicable, please log into the Click™ Research Compliance System, open the study's workspace, and view the "Documents" tab. To obtain consent form(s) stamped with the IRB watermark, select the "Final" PDF version of your consent form(s) as applicable in the "Documents" tab. Please note that the consent form(s) stamped with the IRB watermark must typically be used.

Continuing Review: IRB approval is valid until the expiration date listed above. If the research continues to involve human subjects, you must submit a Continuing Review request at least one month before expiration.

Modifications: Any proposed change or modification with certain limited exceptions discussed below must be reviewed and approved by the IRB prior to implementation of the change. Please submit a Modification request to have the

Figure A-6. Institutional review board approval letter

Figure A-6 (cont'd)

changes reviewed. If changes are made at the time of continuing review, please submit a Modification and Continuing Review request.

New Funding: If new external funding is obtained to support this study, a Modification request must be submitted for IRB review and approval before new funds can be spent on human research activities, as the new funding source may have additional or different requirements.

Immediate Change to Eliminate a Hazard: When an immediate change in a research protocol is necessary to eliminate a hazard to subjects, the proposed change need not be reviewed by the IRB prior to its implementation. In such situations, however, investigators must report the change in protocol to the IRB immediately thereafter.

Reportable Events: Certain events require reporting to the IRB. These include:

- Potential unanticipated problems that may involve risks to subjects or others
- Potential noncompliance
- Subject complaints
- Protocol deviations or violations
- Unapproved change in protocol to eliminate a hazard to subjects
- Premature suspension or termination of research
- Audit or inspection by a federal or state agency
- New potential conflict of interest of a study team member
- Written reports of study monitors
- Emergency use of investigational drugs or devices
- Any activities or circumstances that affect the rights and welfare of research subjects
- Any information that could increase the risk to subjects

Please report new information through the study's workspace and contact the IRB office with any urgent events. Please visit the Human Research Protection Program (HRPP) website to obtain more information, including reporting timelines.

Personnel Changes: Key study personnel must be listed on the MSU IRB application for expedited and full board studies and any changes to key study personnel must to be submitted as modifications. Although only key study personnel need to be listed on a non-exempt application, all other individuals engaged in human subject research activities must receive and maintain current human subject training, must disclose conflict of interest, and are subject to MSU HRPP requirements. It is the responsibility of the Principal Investigator (PI) to maintain oversight over all study personnel and to assure and to maintain appropriate tracking that these requirements are met (e.g. documentation of training completion, conflict of interest). When non-MSU personnel are engaged in human research, there are additional requirements. See HRPP Manual Section 4-10, Designation as Key Project Personnel on Non-Exempt IRB Projects for more information.

2

Figure A-6 (cont'd)

Prisoner Research: If a human subject involved in ongoing research becomes a prisoner during the course of the study and the relevant research proposal was not reviewed and approved by the IRB in accordance with the requirements for research involving prisoners under subpart C of 45 CFR part 46, the investigator must promptly notify the IRB.

Site Visits: The MSU HRPP Compliance office conducts post approval site visits for certain IRB approved studies. If the study is selected for a site visit, you will be contacted by the HRPP Compliance office to schedule the site visit.

For Studies that Involve Consent, Parental Permission, or Assent Form(s):

Use of IRB Approved Form: Investigators must use the form(s) approved by the IRB and must typically use the form with the IRB watermark.

Copy Provided to Subjects: A copy of the form(s) must be provided to the individual signing the form. In some instances, that individual must be provided with a copy of the signed form (e.g. studies following ICH-GCP E6 requirements). Assent forms should be provided as required by the IRB.

Record Retention: All records relating to the research must be appropriately managed and retained. This includes records under the investigator's control, such as the informed consent document. Investigators must retain copies of signed forms or oral consent records (e.g., logs). Investigators must retain all pages of the form, not just the signature page. Investigators may not attempt to de-identify the form; it must be retained with all original information. The PI must maintain these records for a minimum of three years after the IRB has closed the research and a longer retention period may be required by law, contract, funding agency, university requirement or other requirements for certain studies, such as those that are sponsored or FDA regulated research. See HRPP Manual Section 4-7-A, Recordkeeping for Investigators, for more information.

Closure: If the research activities no longer involve human subjects, please submit a Continuing Review request, through which study closure may be requested. Human subject research activities are complete if there is no further interactions or interventions with human subjects and/or no further analysis of identifiable private information.

For More Information: See the HRPP Manual (available at hrpp.msu.edu).

Contact Information: If we can be of further assistance or if you have questions, please contact us at 517-355-2180 or via email at IRB@msu.edu. Please visit hrpp.msu.edu to access the HRPP Manual, templates, etc.

Expedited Category. Please see the appropriate research category below for the full regulatory text.

Expedited 1. Clinical studies of drugs and medical devices only when condition (a) or (b) is met.

3

(a) Research on drugs for which an investigational new drug application (21 CFR Part 312) is not required. (Note: Research on marketed drugs that significantly increases the risks or decreases the acceptability of the risks associated with the use of the product is not eligible for expedited review.)
(b) Research on medical devices for which (i) an investigational device exemption application (21 CFR Part 812) is not required; or (ii) the medical device is cleared/approved for marketing and the medical device is being used in accordance with its cleared/approved labeling.

Expedited 2. Collection of blood samples by finger stick, heel stick, ear stick, or venipuncture as follows:
(a) from healthy, nonpregnant adults who weigh at least 110 pounds. For these subjects, the amounts drawn may not exceed 550 ml in an 8 week period and collection may not occur more frequently than 2 times per week; or
(b) from other adults and children, considering the age, weight, and health of the subjects, the collection procedure, the amount of blood to be collected, and the frequency with which it will be collected. For these subjects, the amount drawn may not exceed the lesser of 50 ml or 3 ml per kg in an 8 week period and collection may not occur more frequently than 2 times per week.

Expedited 3. Prospective collection of biological specimens for research purposes by noninvasive means.
Examples: (a) hair and nail clippings in a nondisfiguring manner; (b) deciduous teeth at time of exfoliation or if routine patient care indicates a need for extraction; (c) permanent teeth if routine patient care indicates a need for extraction; (d) excreta and external secretions (including sweat); (e) uncannulated saliva collected either in an unstimulated fashion or stimulated by chewing gumbase or wax or by applying a dilute citric solution to the tongue; (f) placenta removed at delivery; (g) amniotic fluid obtained at the time of rupture of the membrane prior to or during labor; (h) supra- and subgingival dental plaque and calculus, provided the collection procedure is not more invasive than routine prophylactic scaling of the teeth and the process is accomplished in accordance with accepted prophylactic techniques; (i) mucosal and skin cells collected by buccal scraping or swab, skin swab, or mouth washings; (j) sputum collected after saline mist nebulization.

Expedited 4. Collection of data through noninvasive procedures (not involving general anesthesia or sedation) routinely employed in clinical practice, excluding procedures involving x-rays or microwaves. Where medical devices are employed, they must be cleared/approved for marketing. (Studies intended to evaluate the safety and effectiveness of the medical device are not generally eligible for expedited review, including studies of cleared medical devices for new indications.)
Examples: (a) physical sensors that are applied either to the surface of the body or at a distance and do not involve input of significant amounts of energy into the subject or an invasion of the subject's privacy; (b) weighing or testing sensory acuity; (c) magnetic resonance imaging; (d) electrocardiography, electroencephalography, thermography, detection of naturally occurring radioactivity, electroretinography, ultrasound, diagnostic infrared imaging, doppler blood flow, and echocardiography; (e) moderate exercise, muscular strength

testing, body composition assessment, and flexibility testing where appropriate given the age, weight, and health of the individual.

Expedited 5. Research involving materials (data, documents, records, or specimens) that have been collected, or will be collected solely for nonresearch purposes (such as medical treatment or diagnosis). (NOTE: Some research in this category may be exempt from the HHS regulations for the protection of human subjects. 45 CFR 46.101(b)(4). This listing refers only to research that is not exempt.)

Expedited 6. Collection of data from voice, video, digital, or image recordings made for research purposes.

Expedited 7. Research on individual or group characteristics or behavior (including, but not limited to, research on perception, cognition, motivation, identity, language, communication, cultural beliefs or practices, and social behavior) or research employing survey, interview, oral history, focus group, program evaluation, human factors evaluation, or quality assurance methodologies. (NOTE: Some research in this category may be exempt from the HHS regulations for the protection of human subjects. 45 CFR 46.101(b)(2) and (b)(3). This listing refers only to research that is not exempt.)

Expedited 8. Continuing review of research previously approved by the convened IRB as follows:
(a) where (i) the research is permanently closed to the enrollment of new subjects; (ii) all subjects have completed all research-related interventions; and (iii) the research remains active only for long-term follow-up of subjects; or
(b) where no subjects have been enrolled and no additional risks have been identified; or
(c) where the remaining research activities are limited to data analysis.

Expedited 9. Continuing review of research, not conducted under an investigational new drug application or investigational device exemption where categories two (2) through eight (8) do not apply but the IRB has determined and documented at a convened meeting that the research involves no greater than minimal risk and no additional risks have been identified.

APPENDIX C: Institutional Review Board Consent Forms

Consent Form for Whole Research

Research Participant Information and Consent Form

You are being asked to participate in a research study. Researchers are required to provide a consent form to inform you about the research study, to convey that participation is voluntary, to explain risks and benefits of participation, and to empower you to make an informed decision. You should feel free to ask the researchers any questions you may have.

Study Title: Network Interventions on Engineering Projects

1. PURPOSE OF RESEARCH

The purpose of this research study is to advance our understanding about how optimizing interactions across disciplinary boundaries in inter-organizational Architecture, Engineering, and Construction project teams can improve sustainability outcomes.

2. WHAT YOU WILL DO

- You will fill out a short demographics survey at the beginning of our study.
- You will give permission to collect project data via the following during the course of this AEC project:
    - Your project specific e-mail exchange information captured via email headers (limited to subject, sender, recipient(s), and date/time) will be collected. These email headers are stored in your organization's database and will be automatically collected in cooperation with your organization and its IT department/personnel periodically during the course of this project. Any email headers and senders/recipients outside of the scope of this study will be filtered out in this process.

- A member of the research team will join project meetings and record the meetings.
    - Web-based project document sharing platform that will be accessed and observed by the project team.
- Two to four times during this AEC project, you will be asked to:
    - Fill out online surveys to help us assess your processes, network, and team and project performance outcomes and
    - Attend social network intervention meetings.
- Based on the data collected, you might be asked to:
    - Participate in structured interviews that will be possibly audio recorded and
    - Provide artifacts such as LEED checklists and other project documents.

3. POTENTIAL BENEFITS

- The findings of this study will potentially help improve team integration (e.g., interactions among interdisciplinary experts) and optimize sustainable performance outcomes.
- Study results will be shared in the form of an executive summary with the participants. The results can lead to reduced stress at individual level, higher work satisfaction, and follow up works in the long run.

4. POTENTIAL RISKS

There are no foreseeable risks associated with participation in this study.

5. PRIVACY AND CONFIDENTIALITY

- During data analysis your identity will be coded with a random number.
- Your identity will not be disclosed in any report, document, or publication.
- The researchers will keep the collected data in password protected laptops and on MSU Spartan365 Server.

- The researchers will not disclose any specific information about the projects or study participants to the maximum extent allowable by law.
- The MSU Human Research Protection Program may have access to the data. Publications coming out from this study will present the data in aggregate form, so no participant will be identifiable.
- The data will be stored for a minimum of three years after completion of the study.

6. YOUR RIGHTS TO PARTICIPATE, SAY NO, OR WITHDRAW

You have the right to say no to participating in the research. You can stop at any time after it has already started. There will be no consequences if you stop, and you will not be criticized. You will not lose any benefits that you normally receive.

7. COSTS AND COMPENSATION FOR BEING IN THE STUDY

You will not receive money or any other form of compensation for participating in this study.

8. CONTACT INFORMATION

If you have concerns or questions about this study, such as scientific issues, how to do any part of it, or to report an injury, please contact the researchers:

- Dr. Sinem Mollaoglu: SPDC, sinemm@msu.edu, 517-353-3252
- Dr. Dong Zhao: SPDC, dzhao@msu.edu, 517-432-3242
- Dr. Kenneth Frank: College of Education, kenfrank@msu.edu, 517-355-9567.
- Meltem Duva, PhD Student: SPDC, duvamelt@msu.edu, 517-626-4196,

If you have questions or concerns about your role and rights as a research participant, would like to obtain information or offer input, or would like to register a complaint about this study, you may contact, anonymously if you wish, the Michigan State University's Human Research

Protection Program at 517-355-2180, Fax 517-432- 4503, or e-mail irb@msu.edu or regular mail at 4000 Collins Rd, Suite 136, Lansing, MI 48910.

9. DOCUMENTATION OF INFORMED CONSENT

Your signature below means that you voluntarily agree to participate in this research study.

______________________________________ ____________________________
Signature Date

Consent Form for Online Surveys

Research Participant Information and Consent Form

You are being asked to participate in a research study. Researchers are required to provide a consent form to inform you about the research study, to convey that participation is voluntary, to explain risks and benefits of participation, and to empower you to make an informed decision. You should feel free to ask the researchers any questions you may have.

Study Title: Network Interventions on Engineering Projects

1. PURPOSE OF RESEARCH

The purpose of this research study is to advance our understanding about how optimizing interactions across disciplinary boundaries in inter-organizational Architecture, Engineering, and Construction project teams can improve sustainability outcomes.

2. WHAT YOU WILL DO

- Two to four times during this AEC project, you will be asked to fill out an online survey to help us assess your processes, network, and team and project performance outcomes.

3. POTENTIAL BENEFITS

- The findings of this study will potentially help improve team integration (e.g., interactions among interdisciplinary experts) and optimize sustainable performance outcomes.
- Study results will be shared in the form of an executive summary with the participants. The results can lead to reduced stress at individual level, higher work satisfaction, and follow up work in the long run.

4. POTENTIAL RISKS

There are no foreseeable risks associated with participation in this study.

5. PRIVACY AND CONFIDENTIALITY

- During data analysis your identity will be coded with a random number.
- Your identity will not be disclosed in any report, document, or publication.
- The researchers will keep the collected data in password protected laptops and on MSU Spartan365 Server.
- The researchers will not disclose any specific information about the projects or study participants to the maximum extent allowable by law.
- The MSU Human Research Protection Program may have access to the data. Publications coming out from this study will present the data in aggregate form, so no participant will be identifiable.
- The data will be stored for a minimum of three years after completion of the study.

6. YOUR RIGHTS TO PARTICIPATE, SAY NO, OR WITHDRAW

You have the right to say no to participating in the research. You can stop at any time after it has already started. There will be no consequences if you stop, and you will not be criticized. You will not lose any benefits that you normally receive.

7. COSTS AND COMPENSATION FOR BEING IN THE STUDY

You will not receive money or any other form of compensation for participating in this study.

8. CONTACT INFORMATION

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9. DOCUMENTATION OF INFORMED CONSENT

Your signature below means that you voluntarily agree to participate in this research study.

______________________________	______________________
Signature	Date

Approved by a Michigan State University Institutional Review Board effective 6/9/2022. This version supersedes all previous versions. MSU Study ID STUDY00001064.

APPENDIX D: Intervention Protocol

ENGINEERING PROJECT NETWORKS

Lessons Learned

Final Round

Research Team

Leads: Drs. Sinem Mollaoglu, Dong Zhao, Kenneth Frank

Members: Dr. Angelo Garcia, Meltem Duva (Doctoral Student), Nishchhal Pandey (MS Student)

Support: MSU Undergraduate Students

Study Information

NSF: CMMI 1825678

MSU IRB: 00001064

1. EXECUTIVE SUMMARY

The vision for this research effort is to provide real time feedback to project team members on communication networks to improve performance (**Figure A-7**). In pursuit of this vision, this study identified lessons learned in an Architecture, Engineering, and Construction (AEC) project team.

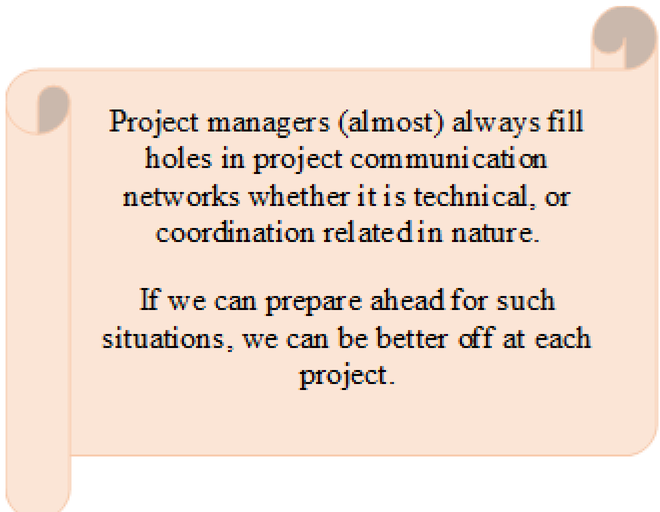


Figure A-7. The vision for the research

For two years, our research team collected data on this case study from multiple sources including project team meeting minutes and meeting observations, project documents, e-mail exchanges, surveys, Unifier, PlanGrid, and interviews with key team members. We analyzed the data using qualitative and quantitative methods. In-person verifications show that communication patterns illustrated in this report accurately reflect project specific team interactions.

The following shows the main findings and practical implications considering mid-sized AEC projects:

1. Project leads working in teams of two for technical and communication coordination is a good practice that can help all primary parties involved to:
   - balance workload,

- avoid communication overload, and
- improve team resilience for unexpected events (e.g., COVID-19, turnover).

Both individuals should be highly experienced in project specific technical domains while their relative authority must be negotiated in response to the immediate demands of the project.

Consider assigning a communication lead with relevant experience for the user group within the Owner organization. Having a "go-to" person overseeing the user-group coordination is beneficial for project team communications and programming.

2. A 'communication support' can be highly beneficial in assisting the project's communication leads.
    - Consider assigning support personnel to communication leads under Designer and General Contractor roles to benefit the whole project team.
3. Staff assignments: The two findings above translate into three key staff assignments for Designer and Contractor and two staff assignments for Owner organizations (one from user group) in mid-size projects.
4. Prior working experience reinforces trust between team members and can help improve project team efficiency.
    - Consider bringing people with previous experience on board, especially in key roles such as technical and communication leads and supports.
5. Enhance team resilience through communication practices:
    - Consider having a common network neighbor (involving a third people in the interactions of two individuals) in your key project communications to:
        - improve productivity by compensating for poor communication,
        - strengthen trust among members,

    - promote knowledge transfers, and
    - improve team resilience.

6. Targeted involvement of experts (regardless of their position in the network) can help speed up issue resolution and improve team members' sensitivity towards project priorities.
    - Consider bringing key expertise from outside parties such as subcontractors, consultants, and vendors in a timely manner to project communication network.
    - Instead of relying solely on email communication, consider inviting leads of outside party representatives to face-to-face meetings for targeted discussions.
    - Consider inviting secondary team members to limited and planned sessions during in-person project meetings to:
        - protect them from communication overload and
        - improve their sensitivity towards project priorities.
7. Highest team productivity occurs when team members from all expertise areas and organizations exchange information.
    - Consider project's priority issues and stay adaptive in communications to ensure that relevant experts are engaged regardless of their role, organization, and assignments.
8. Personnel changes are common in project teams. Prior to personnel transitions during project delivery, especially for the high influence roles:
    - Consider having an overlap period between the people that transition in and out of the project team to transfer the necessary know-how and smoothen the process. If there is more than one successor, the roles, responsibilities, and boundaries of these people personnel should be made clear.

Future research envisions automated development of social network-based feedback during project delivery. This way, AEC teams can have access to objective and practical in-process evaluation mechanisms for knowledge sharing and take informed actions to optimize project outcomes.

2. INTRODUCTION

The overall goal of this project is to advance our understanding about how interactions among interdisciplinary experts can help improve AEC project performance. Therefore, this study identified the dynamics of project communication networks in an AEC project as a case study and developed lessons-learned for a successful project delivery. Our team longitudinally collected data on this project for two years from different sources including:

- Weekly project team meeting minutes,
- Meeting observations,
- E-mail exchange data (i.e., only email headers: sender, receiver, time, and subject),
- Surveys,
- Project documents including Unifier and PlanGrid, and
- Interviews with key team members.

Using email exchange information, we drew sociograms (i.e., network visualizations) and analyzed team member interaction patterns in the light of other data. Interviews with key project participants verified that sociograms reflect the communication patterns of the team. To date we facilitated two feedback sessions with this project team and presented lessons learned in written and in person presentation formats. Figure A-8 shows our engagement with the project team based on delivery phases. Using survey data, we measured team performance three times throughout the project delivery. Individual and team performance remained high over three waves of data collection based on these surveys.

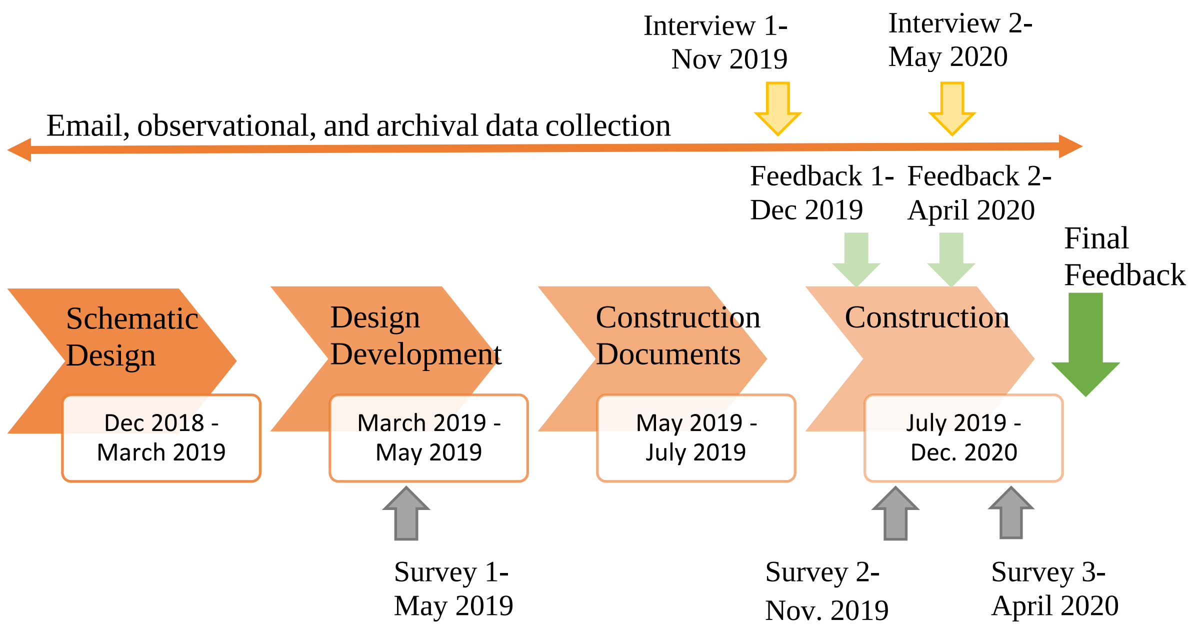
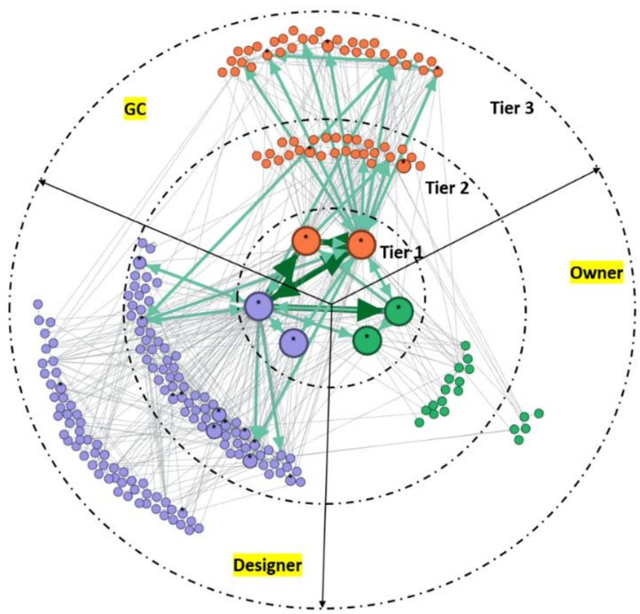


Figure A-8. Project timeline and the research team's engagement with the project

Network visualizations throughout the report are used to illustrate project-based information exchange patterns between project team members. Figure A-9 is organized by organizational structure and includes three roles (i.e., owner, general contractor, designer) across three Tiers:

- Tier 1 includes the main representatives from each role (Owner, Designer or GC) in the project team. They hold decision-making authority associated with their roles for day-to-day operations of the project.
- Tier 2 represents team members from Tier 1 members' home organizations.
- Tier 3 represents all other individuals working on the project including subcontractors, trades, consultants, and other stakeholders.



Dots represent the individuals, and dot size is based on the number of given information during the team meetings. Asterisks indicate the people who attended the weekly project

Links represent the communication between the individuals, and the thickness of the links represent the strength of the communication.

Weak (Monthly) Communication | Moderate (Weekly) Communication | Strong (Daily) Communication

Figure A-9. Project networks based on organizational structure

The network in Figure A-10 is mapped based on communication structure alone. This type of visualization changes over time. A member may become more (core) or less (periphery) central to the network based on their interactions with other team members.

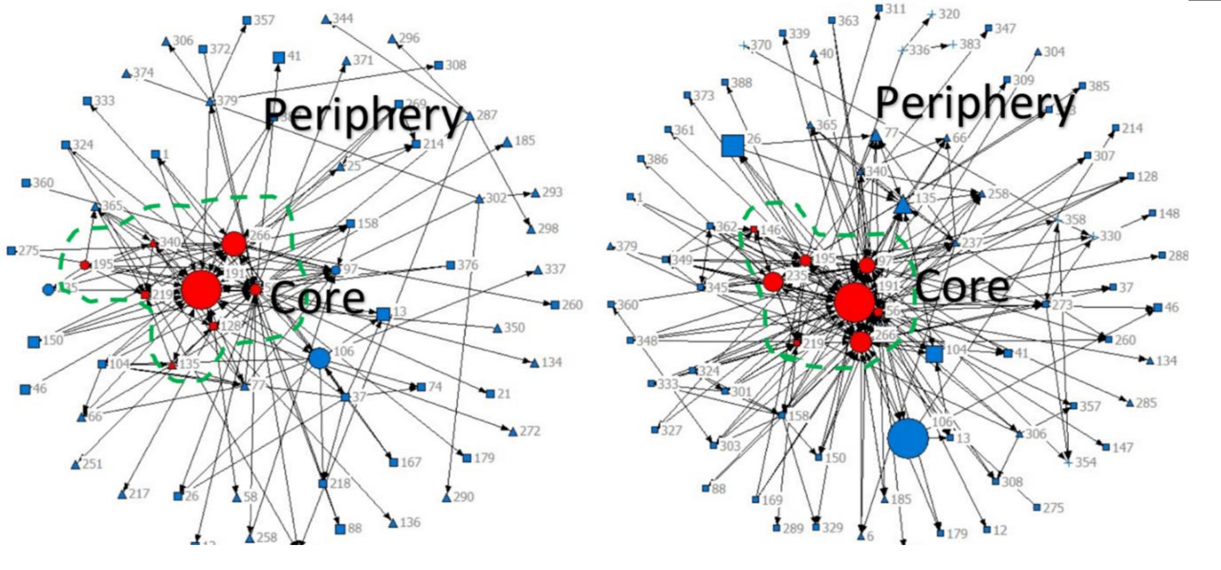


Figure A-10. Project networks based on communication structure: Core and periphery teams

This report presents findings related to:

- Feedback Cycle 1: Phases from Schematic Design to Construction (e.g., Excavation, Earth Retention and Steel Erection)
- Feedback Cycle 2: Construction (e.g., Masonry, MEP Systems)
- Feedback Cycle 3: Construction (e.g., Exterior, Roofing and Landscaping)

Disclaimer:

To ensure participants' confidentiality, figures in the report may have been adjusted and/or belong to other project networks.

3. FEEDBACK CYCLE 1- Phases from Schematic Design to Construction

This cycle covers December 2018 through December 2019, including the phases:

- Schematic design,
- Design development,
- Construction documents, and
- The first 5 months of construction (e.g., excavation, earth retention and steel erection).

3.1. Engagement Affects Productivity

- Team productivity is parallel with engagement (Figure A-11).
    - Low engagement leads to low productivity down the line. In other words, when the engagement slows down, we anticipate that slowdown in productivity in a couple weeks.
    - Highest team productivity occurs when team members from all Tiers and different areas of expertise (e.g., architecture, construction, and mechanical engineering) exchange information.
- Engagement can also help avoid high peaks and deep dips in productivity, providing a steady production flow and less stress on project teams and leaders.

Sample Scenario

During the design process, involvement of the parties below can speed up issue resolution, reduce rework, and improve productivity:

- Architectural team collaborates with a well-represented group of user representatives to identify the end use needs.
- Constructor gives constructability and budget feedback for smoother execution.
- Vendors provides information regarding products, materials, and installation to avoid future conflicts.

Figure A-11. Engagement vs. Productivity

3.2. Leads in Teams of Two

In Tier 1, under each role, it is ideal to work in teams of two where:

- one person is in the technical lead – making decisions and
- The other person is the communication lead – facilitating key information exchange among immediately relevant areas of expertise to support the technical lead closely (Figure A-12).

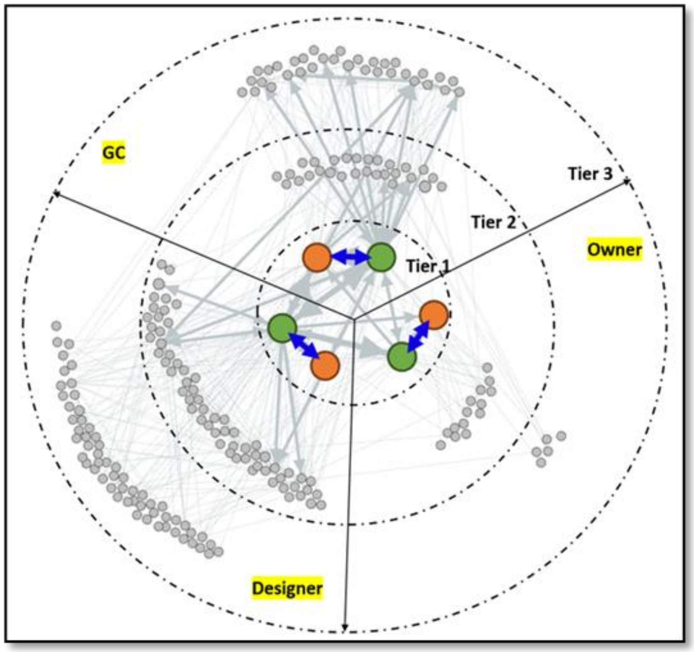


Figure A-12. Leads in teams of two in tier 1

Selection of Leads: Both individuals should be highly experienced in project specific technical domains. It is highly beneficial if at least one of the leads under a given role has prior experience with leads under other roles.

Involvement and Responsibilities: Participating roles should ensure continued engagement of technical, and communication leads of two in Tier 1 throughout project delivery and make their responsibilities clear for the whole team.

Active Engagement: The leads should stay intentional and active during project delivery to keep communication load as balanced as possible between the two leads.

Lead for project team communication coordination: Depending on the phase of project delivery (design, construction), project team communication coordination should be spearheaded by the designer or the contractor's project management leads.

3.3. Roles for Communication Coordination Lead and Support

Communication lead and support in the project team should:

- Carry the personality traits and experience to facilitate the communication exchange process and not only keep minutes and distribute to the team (Figure A-13).

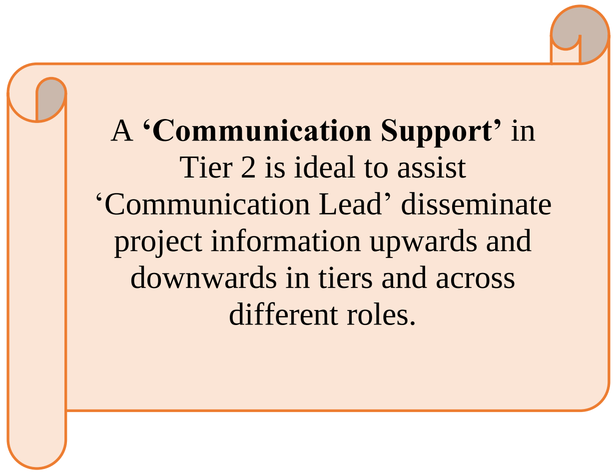


Figure A-13. Role for a communication support

- Consider project’s priority issues and ensure that related expertise areas across Tiers and roles are connected (Figure A-14)
    - Find the holes in the communication network and reach out to immediately relevant experts before tasks fall behind schedule (Figure A-15).
    - Be intentional in activating sub-teams in Tiers 2 and 3 within their role to prepare for upcoming issues. This can help reduce the amount of information overload for all parties (Figure A-16).

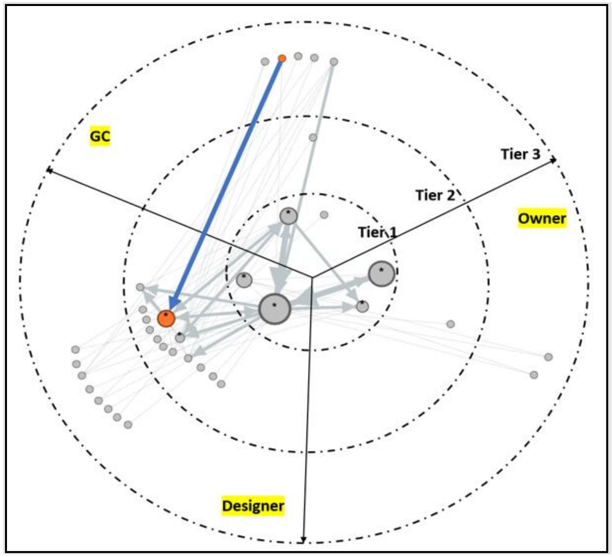


Figure A-14. Orange colored circles connected across Tier 2 of owner and Tier 3 of designer roles, showing same expertise areas with direct communication link.

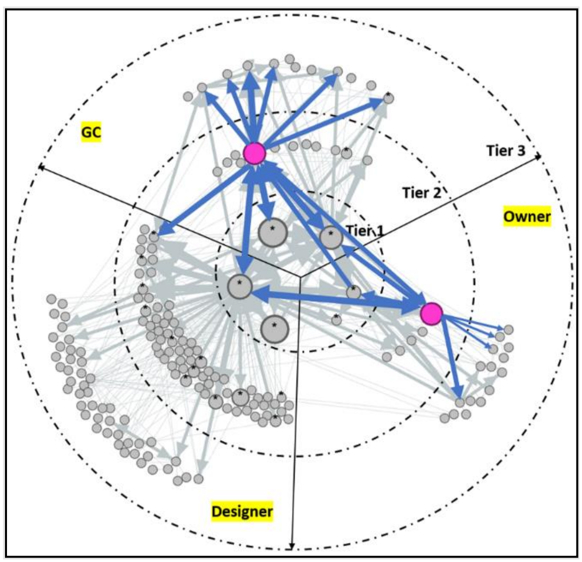


Figure A-15. Communication supports filling the holes, capturing information, and disseminating upwards and downwards across tiers.

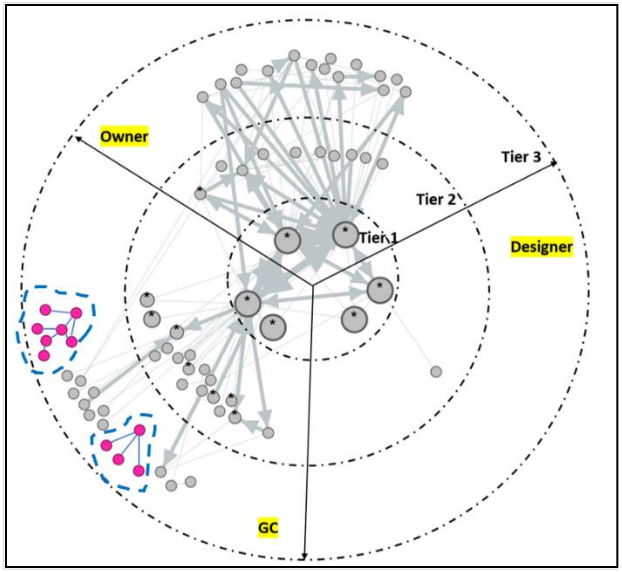


Figure A-16. Sub-teams in Tier-3 are getting ready for the upcoming issues.

3.4. Core Team Members

Core team members should stay adaptive in their communication exchanges with others representing the same expertise area regardless of their Tiers and roles (designer, owner, contractor), while keeping project managers in the loop (Figure A-17).

> **Core team members** are identified based on the project communication network. They can be Tier 1 and/or Tier 2 members.

Figure A-17. Core team members

- They should NOT:
  - stay static within their Tier or role in their project related communications; or
  - depend on Tier 1 members to facilitate and/or initiate information exchanges when the relevant project issues are on the team's radar.

- Core members act adaptively in their communications especially under deadline pressures and not necessarily regularly. Regular practice of this behavior can help avoid bottlenecks and schedule slippages.

3.5. Preparation for Transitions

Phase transitions: While the project moves into a new phase (e.g., from design development to construction documents phase), the communication network does not necessarily follow the same progress. During transitions, team members might become overloaded taking on new roles in addition to continuing ones.

- Key personnel for communication distribution in project teams should have plans and personnel in place to balance the technical and coordination workload during such transitions to avoid overload (Figure A-18).

Personnel transitions: Personnel changes are common in project teams. For smooth transition:

- overlap in work for a period between the people that transition in and out of the project team and,
- plan for transitions considering project phase, personnel experience, and personality, whenever possible.
  - Change in the middle of the project, especially in high influence roles creates a learning curve within the teams for communication dynamics, adds additional load to project managers (PM), and can adversely impact outcomes.

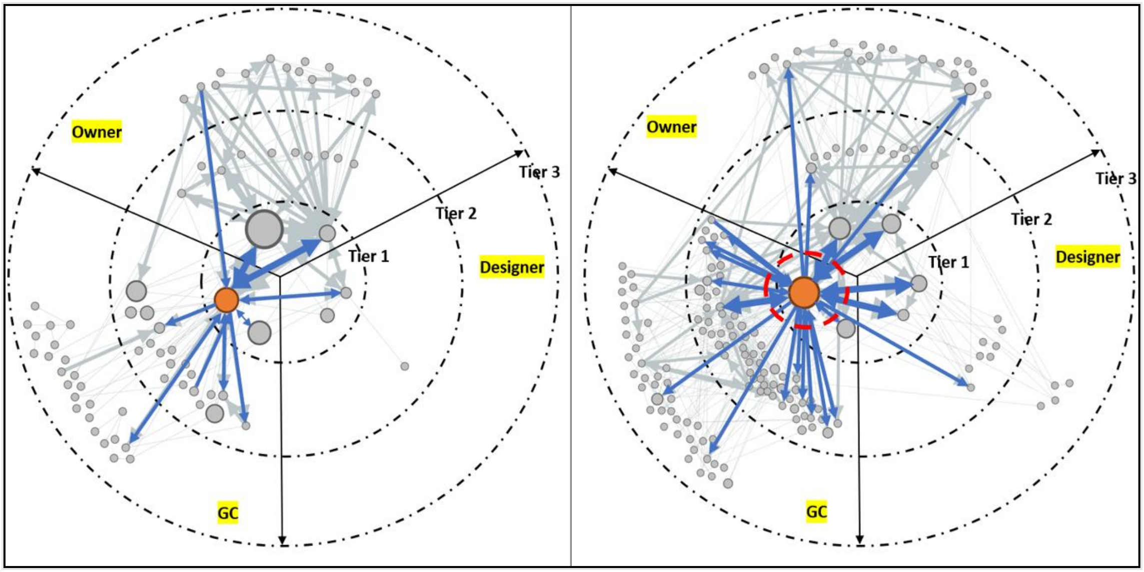


Figure A-18. Load increase on the node after phase transition

3.6. Overload and Support

Communication overload in projects leads to performance deficiencies.

Overload for periphery (less central) members: PMs should look at optimal times, ways, and amounts to involve periphery team members in project meetings and communication network via emails etc. to maximize their performance (Figure A-19).

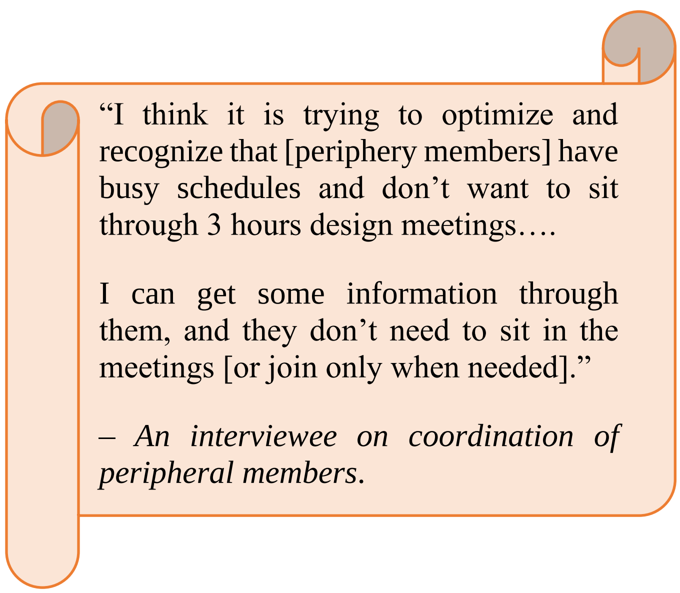


Figure A-19. Overload and support

Overload for leads: In assigning PMs and their support staff, organizations should consider project specific technical experience, personality traits, and overall workload.

- When a PMs in lead of project team communication coordination, he/she should be supported by staff in this position that holds sufficient technical experience specific to the project and the personality to fulfill network holes when needed.
  - If that is lacking, the PM's workload outside of the project should be carefully evaluated to avoid overload, burn out, and less than optimal performance.
- Organizational assignment of the two leads as described is necessary but may not be enough. The leads should stay intentional and active during project delivery in keeping communication load in the project network as balanced as possible between the two leads. If balance is tilted (Figure A-20).
  - The over-loaded lead should make conscious efforts to delegate to support and other lead in Tier 1.
  - The under-loaded lead (compared to the over-loaded lead in the project team communication network) should reach out to the other lead to make structural changes to handling information.
- Co-location is a good strategy in projects that are worth the investment to reduce communication overload using various mediums of technology.

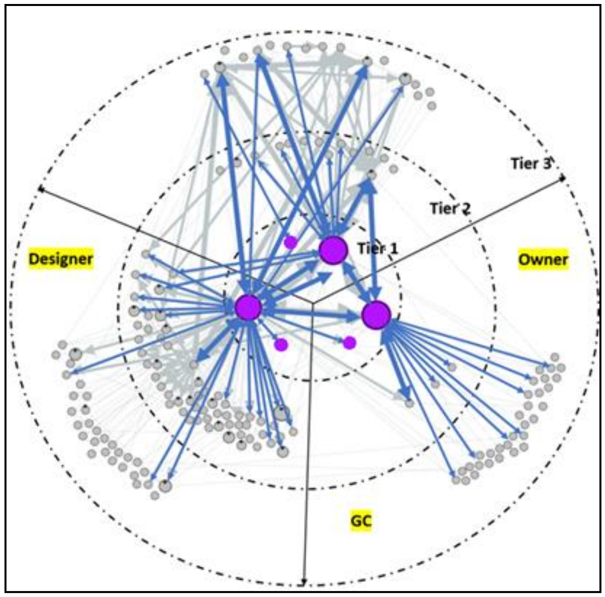


Figure A-20. Unbalanced leads in tier 1 under owner, designer, and GC pies

4. FEEDBACK CYCLE 2- Construction

This cycle covers January 2020 through April 2020, between the 6th - 9th months of Construction Phase (e.g., Masonry, MEP Systems).

4.1. Closed Triads Shifted to Tier 2

> **Closed triads in networks** represent high cooperation and close engagement among multiple actors.

Figure A-21. Closed triads in networks

After construction phase started in this project, we observed (Figure A-21):

- Close engagement of "communication/coordination supports" in Tier 2 in addition to Tier 1 leads for Designer and GC roles, and
- No change in "communication/ coordination lead/ support" for Owner role.

Closed triads expanded to Tiers 2 at this stage while staying in Tier 1 on the owner's side (Yellow lines in Figure A-22*)*.

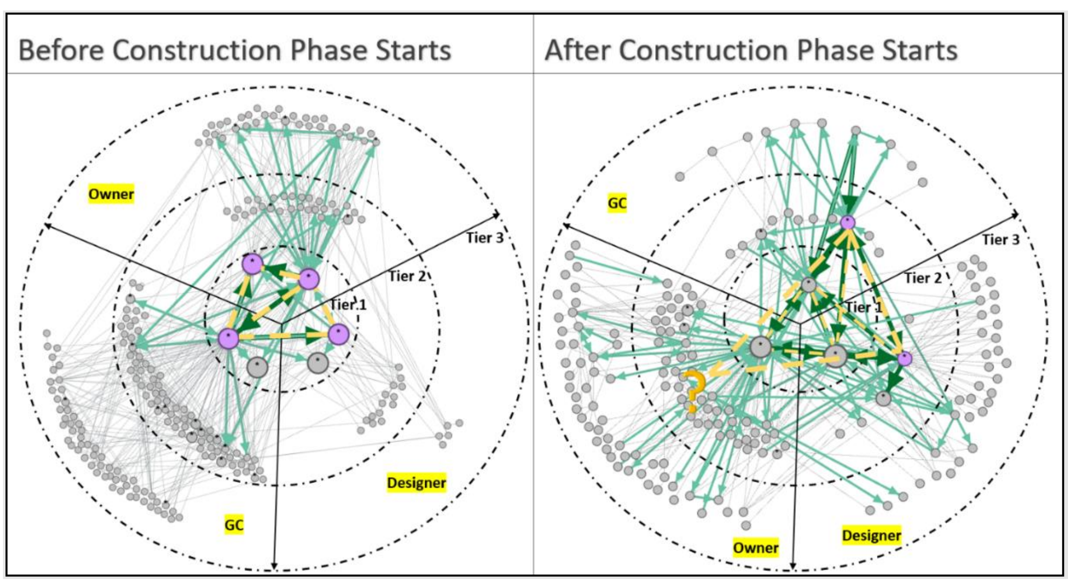


Figure A-22. Closed triads expanded to tiers 2 under designer and GC role

4.2. Targeted Engagement of Tier 3 Members

During construction, experts come in and go out of the project information exchange network on a need basis depending on the phase of the project, especially from Tier 3 (Figure A-23). Enabling targeted engagement of Tier 3 members:

- Help resolve specific issues by bringing Tier 3 team members' key information and expertise in a timely manner,
- and help speed up the resolution of project related issues and therefore enhance productivity.

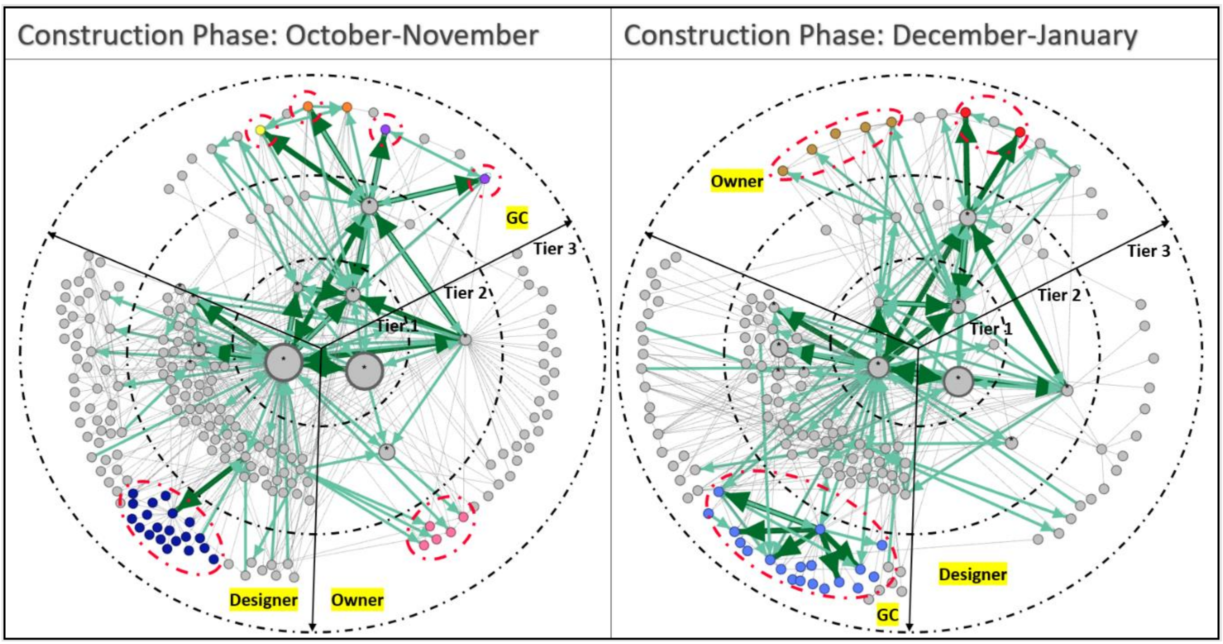


Figure A-23. Targeted engagement: Parties coming-in and going-out of the project information exchange network based on project needs during construction phase

5. FEEDBACK CYCLE 3- Construction

Cycle 3 covers May 2020 through October 2020, the last six months of the construction phase until the substantial completion date (e.g., exterior, roofing, and landscaping) (Figure A-24).

> **Kudos!** Survey results showed that this project team and individuals showed good performance throughout the project delivery.

Figure A-24. Team performance

5.1. Individual and Team Performance Remained High

Figure A-25 shows the average performance for individuals and the whole team per survey responses (question relating to contribution to project execution, communication and coordination skills, adaptation to changes, and innovation etc.)

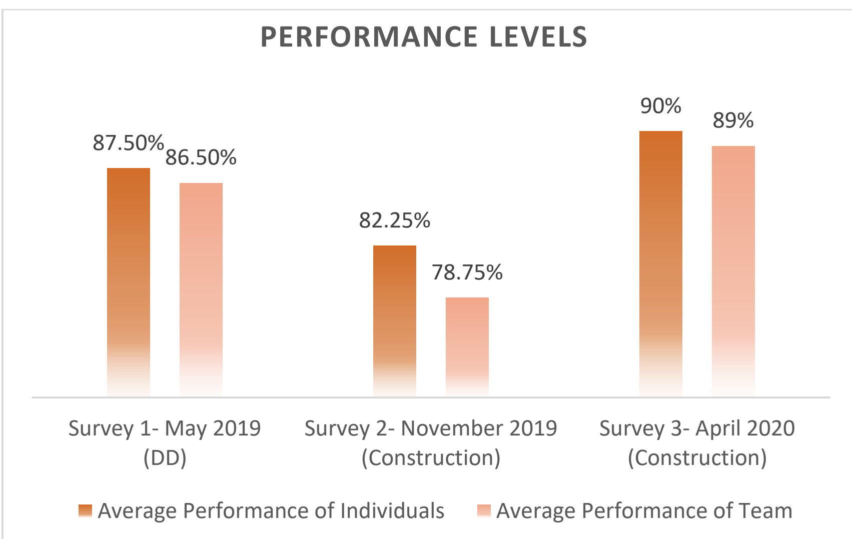


Figure A-25. Performance levels based on survey responses

5.2. Close Engagement Among Key Personnel Throughout Project Delivery

Triangular communication patterns
promote knowledge transfer and strengthen trust among members.

This can help resolve time sensitive issues and bring people on the same page.

Figure A-26. Triangular communication patterns

- In this project, triangular communication patterns frequently show up across different organizational groups and Tiers, including Tier 3 consultants and subcontractors (Figure A-26, Figure A-27).

Design Phase (12.18-07.19)   Construction Phase (07.19-10.20)   Towards End (09.20)

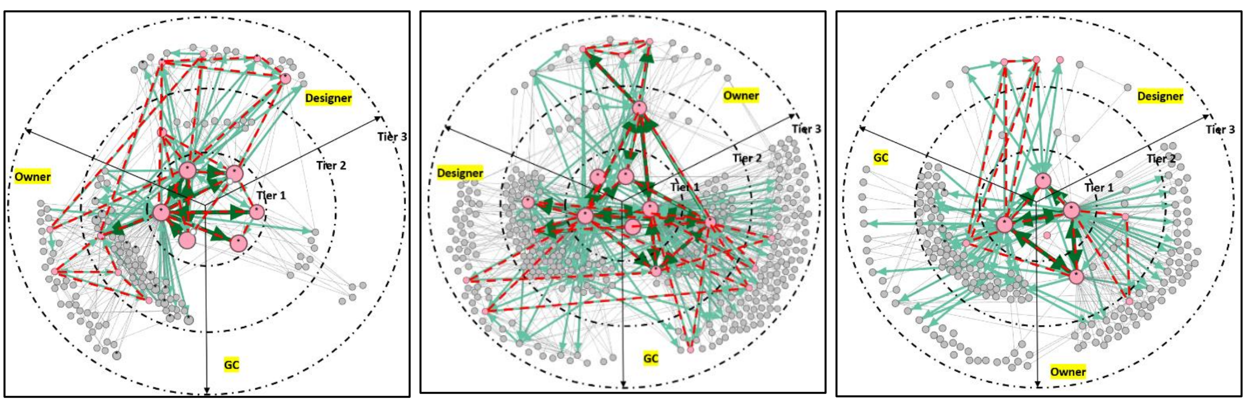


Figure A-27. Triads expand and shrink based on the project schedule and needs

Many triangles exist between owner and designer roles during design phase and help improve goal alignment early in the delivery process.

- Triangular patterns expand to include the general contractor in construction phase.
- The prevalence of triangles shrinks towards the end of construction phase yet remains among Tier 1 members and Tier 3 Designer members.

5.3.Tier 2 Support Helped Maintain Communication Load

When project leaders are overloaded with information, or otherwise unavailable, Tier 2 communication supports proactively take on the communication load to coordinate information exchange with relevant team members (Figure A-28).

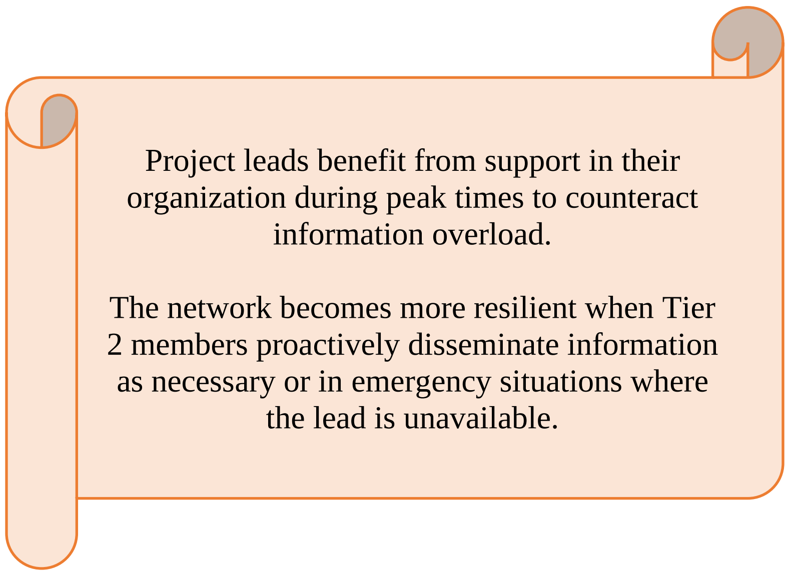


Figure A-28. Communication supports in tier 2

- Tier 2 communication supports in the Designer and General Contractor roles supported project leads by facilitating communication across Tiers and core organizational groups (Figure A-29). These individuals shift from the periphery to the core of the network by increasing their interactions within and across boundaries. They disseminate information upwards and downwards, across different Tiers and roles.
- The lack of Tier 2 support in the Owner organizational group placed the entire communication load on the project lead. Such conditions may result in negative consequences and can affect the project network resilience adversely if the team lead is unable to serve as the hub of information. Having communication support in Tier 2 is

beneficial as communication overload in projects can lead to less-than-optimal performance.

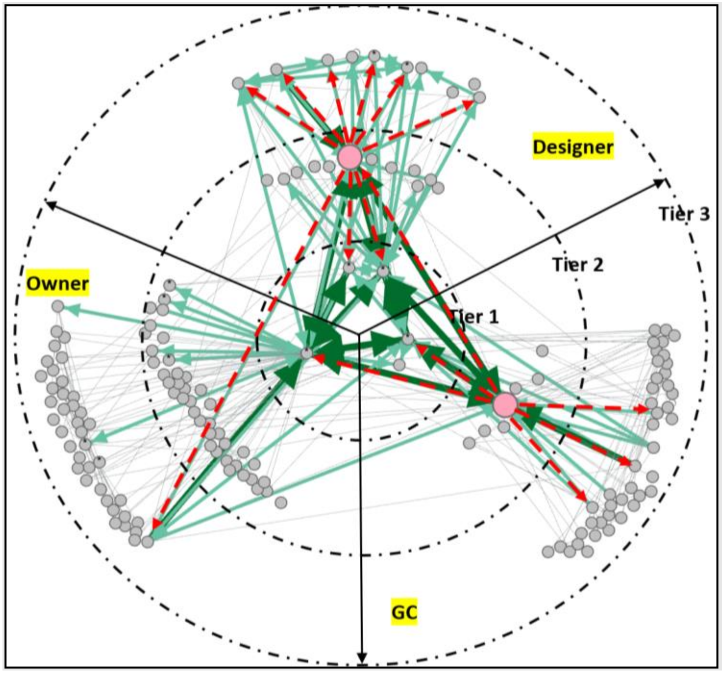


Figure A-29. Communication support from tier 2 members

5.4.Expertise Integration Per Project Needs

Project teams should effectively engage with third parties, consultants, and vendors.

When needed, instead of relying solely on email communication, having them join the face-to-face meetings can help improve experts' sensitivity towards the project and speed up issue resolution.

Figure A-30. Expertise integration

High expertise integration from third parties (vendors, design consultants, etc.) is necessary at times in project delivery (Figure A-30).

- These individuals are likely to be in the periphery of the communication network when information exchange is mapped regarding day-to-day decision making.
- When their expertise is needed, a lack of established communication patterns may hinder their ability to share knowledge with the appropriate recipients.

See Figure A-31 for examples of small clusters of members who communicate primarily with those close to them yet remain isolated from the broader network.

To leverage the knowledge and expertise of specialists, project leads should consider:

- Identifying members who communicate through email alone and do not interact in face-to-face meetings or use communication technology that provides a richer interactive experience (phone calls, zoom meetings, etc.).
- Including experts in face-to-face team meetings even after the completion of design phase when necessary to improve their sensitivity towards the project, help things move and therefore, enhance team performance.

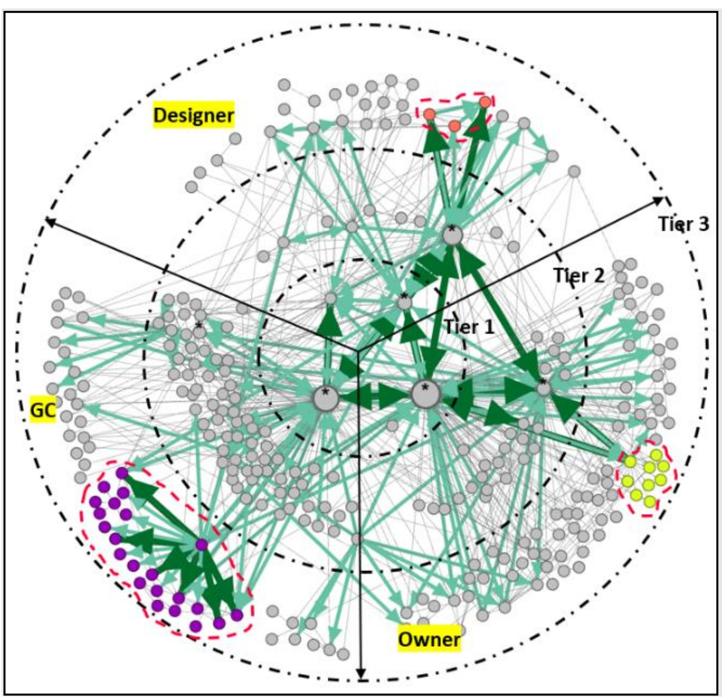


Figure A-31. Team members communicating through email alone

6. CONCLUSION

The overall goal of this project is to advance our understanding about how interactions among interdisciplinary experts can help improve AEC project performance. Towards this goal, this study examined the dynamics of project communication networks in an AEC project as a case study and developed lessons learned.

To achieve its aims, our research team longitudinally collected data on this project for two years from different sources of data and analyzed them using mixed methods. Results showed that individual and team performance remained high over project delivery. The following shows the main findings relating to the project communication network:

- **Project leads working in teams of two** for technical and communication coordination is a good practice that can help all primary parties involved to:
  - balance workload,
  - avoid communication overload, and
  - improve team resilience for unexpected events (e.g., COVID-19, turnover).
- A **'communication support'** can be highly beneficial in assisting the project's communication leads.
- **Staff assignments:** The two findings above translate into three key staff assignments for Designer and Contractor and two staff assignments for Owner organizations (one from user group) in mid-size projects.
- **Prior working experience** reinforces trust between team members and can help improve project team efficiency.
- Enhance team resilience through communication practices.

- **Targeted involvement of experts** (regardless of their position in the network) can help speed up issue resolution and improve team members' sensitivity towards project priorities.
- **Highest team productivity** occurs when team members from all expertise areas and organizations exchange information.
- **Personnel changes** are common in project teams. Prior to personnel transitions during project delivery, especially for the high influence roles, consider having an overlap period between the people that transition in and out of the project team to transfer the necessary know-how and smoothen the process. If there is more than one successor, the roles, responsibilities, and boundaries of these people personnel should be made clear.

Future research will fully automate development of social network-based evaluation of project teams and feedback mechanisms during project delivery. This way, AEC teams can have access to objective and practical in-process evaluation mechanisms for interdisciplinary team interactions and take informed actions for corrections when and if needed to optimize project outcomes.