Expertise Flows and Network Structures in AEC Project Teams

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ABSTRACT

Architectural, Engineering, and Construction (AEC) project team networks frequently increase the density of information sharing ties to improve team performance. However, increased density might not result in team members receiving adequate information to collaborate towards common goals. There is a need to examine how network ties should be set up to manage information flows. Thus, the research goal is to explore the features of information sharing networks and their relationship with team performance in AEC projects. To achieve this goal, we collected communication data from an AEC project team with 179 members involved in total during the schematic design phase. Then, we performed social network analysis using Gephi and UCINET software. Results suggest that AEC project team networks are dynamic and adopt a core-periphery structure to share information early in project delivery. Including civil and mechanical subcontractors into the core subnetwork to collaborate with owners, designers, and general contractors can improve team performance. The study's contribution to the body of knowledge is expanding our understanding of the characteristics and evolution of information sharing networks in AEC projects for optimized team performance.

INTRODUCTION

Characterized by technical systems with high levels of interdependency, Architecture, Engineering, and Construction (AEC) projects demand increased levels of design collaboration and integration between structural, envelope, mechanical, electrical, and architectural systems during design (Riley et al., 2004). For decades, efforts from the AEC industry have been directed to improve systematic integration; however, the highly fragmented nature of AEC project teams makes such effort difficult (Korkmaz and Singh, 2001). AEC project teams gather experts from different disciplines and organizations who never worked together before. These experts form an information sharing network to collaborate toward common goals, but often fail to share and use each other's expertise in a timely manner (Mollaoglu et al., 2013). To address team fragmentation, AEC project teams increase network density (i.e., portion of potential ties that actually exist) for information exchange promoting practices such as trust or shared values among team members (Chinowsky et al., 2008, 2011), boundary spanners for coordination across disciplines (Iorio et al., 2012), cohesive subgroups for integrated building design (Garciacortes, 2017) or collaborative information technologies such as building information modeling (BIM) (Al Hattab and Hamzeh, 2018). However, increased network density might be problematic as different networks may possess equal density while supplying team members with different information. There is a knowledge gap regarding how ties should be distributed within project team networks to facilitate expertise flows during project delivery and enhance team collaboration.

Hence, the goal of this paper is to examine the features of information sharing networks and team performance in AEC projects. To achieve this goal, we collected archival, observational, and email communication data from an AEC project team with a total of 179 members involved during the schematic design phase. We analyzed the project meeting minutes (i.e., archival data) to detect key episodes during this phase and determine team performance based on number of days and responsible parties to resolve project issues. Using the observational and email exchange data, we performed social network analysis using Gephi and UCINET software. Results suggest that AEC project teams are dynamic and develop an information sharing network with a core-periphery structure during early stages of project delivery. Including members such as civil and mechanical engineers in addition to owner, designer, and general contractor representatives into the core network can help optimize expertise flows and team productivity.

BACKGROUND

AEC project teams bring together experts with little or no previous connections that move from formation to collaboration stages quickly. Most common barriers for team information flows include lack of trust and common knowledge across disciplinary and organizational boundaries (Reagans and McEvily, 2003). Failing to overcome these barriers can lead to team fragmentation in which building systems are overdesigned in isolation and often conflict with one another (Magent et al., 2009). Highly integrated project teams continuously exchange information for enhancing team performance (Katzenbach and Smith, 2005; Chinowsky et al., 2008). Via social networks, team members' information sharing behaviors can be mapped and analyzed mathematically to assess team collaboration (Hanneman and Riddle, 2005) and further examined to evaluate impacts on team productivity and work plan variations (Abbsaian-Hosseini et al. 2017).

Common organizational network structures might not be adequate to understand information sharing dynamics in AEC project teams which, for every project, develop a unique product with different requirements and team composition (Cross et al., 2002). For example, information sharing networks built upon the transaction-cost theory of organizations might not facilitate optimal project outcomes (Williamson, 1986). Under this theory, AEC project teams establish a fixed network for sharing information and control costs associated with information exchange. Thus, the information sharing network cannot easily adapt to changing project demands. However, AEC project teams might improve their performance if governed by the knowledge-based theory (Grant, 1996). With this approach, AEC project team networks can be dynamic and adapt to project needs. Consequently, team members can use other team members' key information and expertise in a timely manner to improve outcomes.

AEC project team networks can modify their density of ties during project delivery. Higher density levels can improve the chances of team members sharing adequate information for optimal collaboration and integration of various building systems (Chinowsky et al., 2011). If a pair of members participating in network ties develop trust and shared values, then the quality of information sharing increases (Chinowsky et al., 2008). The density of ties does not need to be uniformly distributed throughout AEC project team networks. The presence of structural holes around some network positions (e.g, missing interactions between members to whom someone is connected) within the network might help distribute ties while avoiding continuous and unnecessary sharing of repetitive information (Burt, 2004; Tortoriello, 2015). Structural holes within networks can facilitate formation of cohesive subgroups. These subgroups display a high number of internal ties as compared with the number of ties across subgroups (Frank, 1995). In AEC project teams, subgroups (also called cross-functional teams) gather experts from diverse disciplines to develop a common a task (Garciacortes, 2017; Laurent and Leicht, 2019). Boundary spanners from any discipline or organization can emerge to coordinate information sharing across subgroups (Iorio et al., 2012). Nevertheless, early in project delivery, AEC project networks might involve few members forming a single highly dense group, constituting the seed of a network with a core-periphery structure (Borgatti and Everett, 2000; Lipparini, 2013; Rombach et al., 2017). In these networks, members in the core are highly connected and, to develop their tasks, they share information with other members in a peripheral network who are loosely connected to each other.

In summary, AEC project teams can adopt a variety of network structures across project delivery phases to facilitate expertise flows and accomplish project goals. Thus, this study examines features of information sharing networks in AEC project teams along with team productivity during early stages of project delivery.

METHODS

The case study project was a $19 million institutional renovation project located in a Midwest state in the United States delivered via Construction Management at Risk. The project started in September 2018 and is planned to run for 2 years. The design phases in AEC projects are key stages where majority of the interdisciplinary information exchange and decision-making with highest impacts on project and building outcomes take place (AIA, 2007). This paper focuses on the schematic design phase of the case study project and stands as the first part of a longitudinal study. During the schematic design phase, the case study project team included and reached out to 179 members in total for various levels of expertise consultation and involvement from 20 different organizations including owner's representatives, architects, engineers, contactors, subcontractors, and consultants. The research team collected archival, email, and observational data and mapped the interaction patterns among team members to characterize levels of expert participation and communication.

Archival data consisted of project meeting minutes. First, we qualitatively analyzed project meeting minutes to determine important episodes during the schematic design. Among the project goals examined (i.e., cost, schedule, sustainability), cost data provided the breaking points in the timeline; leading to determination of three, one month long, time intervals. Those time intervals guided the analysis of performance (i.e., measured trough team productivity) and communication data. Second, we used NVivo Plus 12 to examine team productivity by determining the longevity of all project issue/action item resolution (e.g., concept estimate, inventory of equipment, accessible seating design) throughout schematic design per responsible party: Owner, designer, general contractor, or all. We created a Gannt chart in which number of days for issues to resolve were categorized per time interval where all issues were treated equally.

E-mail data collected from owner, general contractor, and designer consisted of headers (i.e., sender, receiver, time, and subject) of e-mails exchanged among project participants. Two coders collected observational data in weekly project team meetings where both coders systematically recorded the number of "give information", "ask information" and "other" types of communications for each individual. To ensure intercoder reliability, (a) coders met after each project meeting to merge and compare notes and (b) researchers calculated the rank Spearman correlation between coders original records for each individual observed in project meetings. 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.

To examine and characterize expertise flows in the project network, email exchange data were used as inputs for the Social Network Analyses (SNA). To determine the strength of network ties, we first calculated frequency (i.e., daily, weekly, monthly) of e-mail exchanges among team members. Next, we coded individuals according to: (a) Main roles in the project (i.e., owner, designer, contractor); (b) Tiers of decision - making and operation (Mollaoglu-Korkmaz et al., 2014) where Tier 1 includes the main representatives from each main role in the project team, Tier 2 represents team members from Tier 1 members' home organizations, and Tier 3 represents all other individuals working on the project including subcontractors, trades, consultants, and other stakeholders; and (c) Expertise areas including organizational planning and programming, project planning, project needs and program, project management, architectural design, interior design, landscape design, civil engineering, specialty design, mechanical, electrical, information/audio-video systems, construction, subcontractor, and vendor/other. Expertise in coding was limited to individuals' primary areas used in the case study project. For example, many of the Tier 1 members fell under 'project management' although they also possess other expertise such as construction or architecture.

For SNA, we first used the number of email exchange between team members for each time interval as an input for Gephi. Using the Circle Pack Layout tool, we drew sociograms grouping and coloring nodes (i.e., team members/individuals). Gephi failed to detect subnetworks in the data. Therefore, we ran the data in UCINET to test for core-periphery structures. This software uses Borgatti and Everett's (2000) algorithm which finds the highest correlation between the observed network and a pattern network formed by (1) a core subnetwork where all nodes are connected by bidirectional ties with a strength of one, and (2) a peripheral subnetwork where all nodes are disconnected. We sized the sociogram nodes based on individuals' "give information" scores .which were highly correlated with "ask information" scores ($r = .94$, $p < .001$).

RESULTS

During schematic design, the project team worked on 57 issues. Table 1 shows team productivity based on time intervals and responsible parties. Team productivity was measured using the percentage of total project issues resolved. Total productivity was highest at the second time interval.

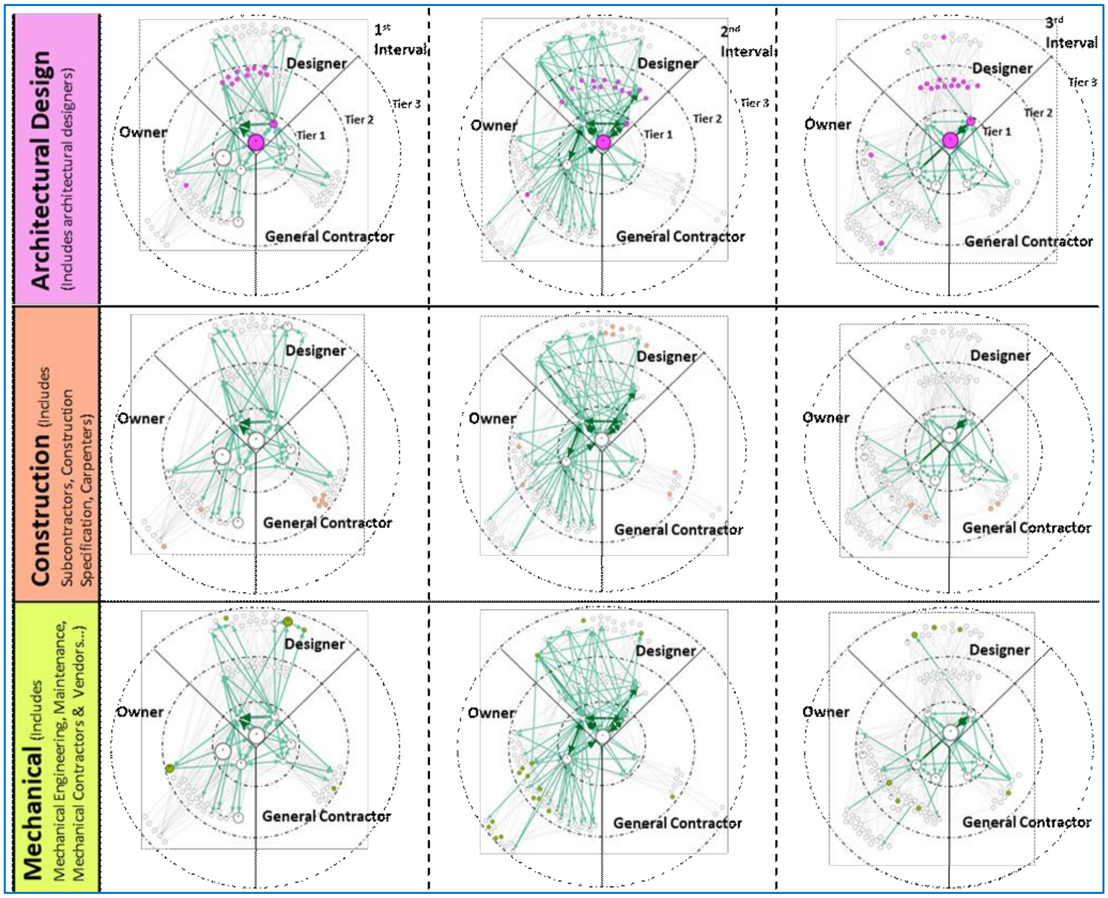
Table 1. Issue Resolution - Team Productivity

Responsible Party by Role	Project Issues Resolved during Case Study Schematic Design Phase — Time Intervals 1	2	3
Owner	0	5%	9%
Designer	12%	44%	14%
Contractor	2%	4%	7%
All	1%	2%	0
Total	15%	55%	30%

Figure 1 illustrates the sociograms drawn with Gephi and organized according to team members' attributes (i.e., role, tier, expertise). The figure displays three of the fifteen primary expertise areas we performed analyses for: Architectural design, construction, and mechanical engineering. The results showed that information exchange across roles mostly occurred within Tier 1 throughout all time intervals. Members in Tiers 2 and 3 barely communicated with each other when they represented different roles in the project. They were mainly connected through Tier 1 members who seemed to act as bridges. Figure 1 shows the following two key network features during Interval 2 when team productivity was highest (Table 1): (1) Members in Tier 1 intensified their communication with members Tiers 2 and 3 (i.e., members from Tier 3 were involved with strong ties to the network only during the second time interval). (2) Network among members under designer role displayed a high number of triadic patterns compared with the other time intervals (i.e., involved three members from at least two different tiers). The two network features above could have helped improve team collaboration across all tiers during Interval 2, especially bringing in direct contributions of Tier 3 experts such as civil and mechanical engineers to the network not only via e-mails but also face-to-face interactions through project team meetings.

Other observations included (a) hierarchical information exchange patterns under owner role across tiers; and (b) Tier 1 representative from designer role with highest 'give information' frequency across all time intervals. However, there were not significant differences in these observations across all time intervals; thus, it was not clear how they could have influenced team productivity.

UCINET identified a core-periphery structured network for each time interval during schematic design (Figure 2). The correlations of the observed core-periphery structures with the ideal pattern structures were $r = .75$, $r = .71$, and $r = .73$ for Intervals 1, 2, and 3 respectively; meaning that there was a core team working cohesively at every time interval. This core team was composed of eight members, although they

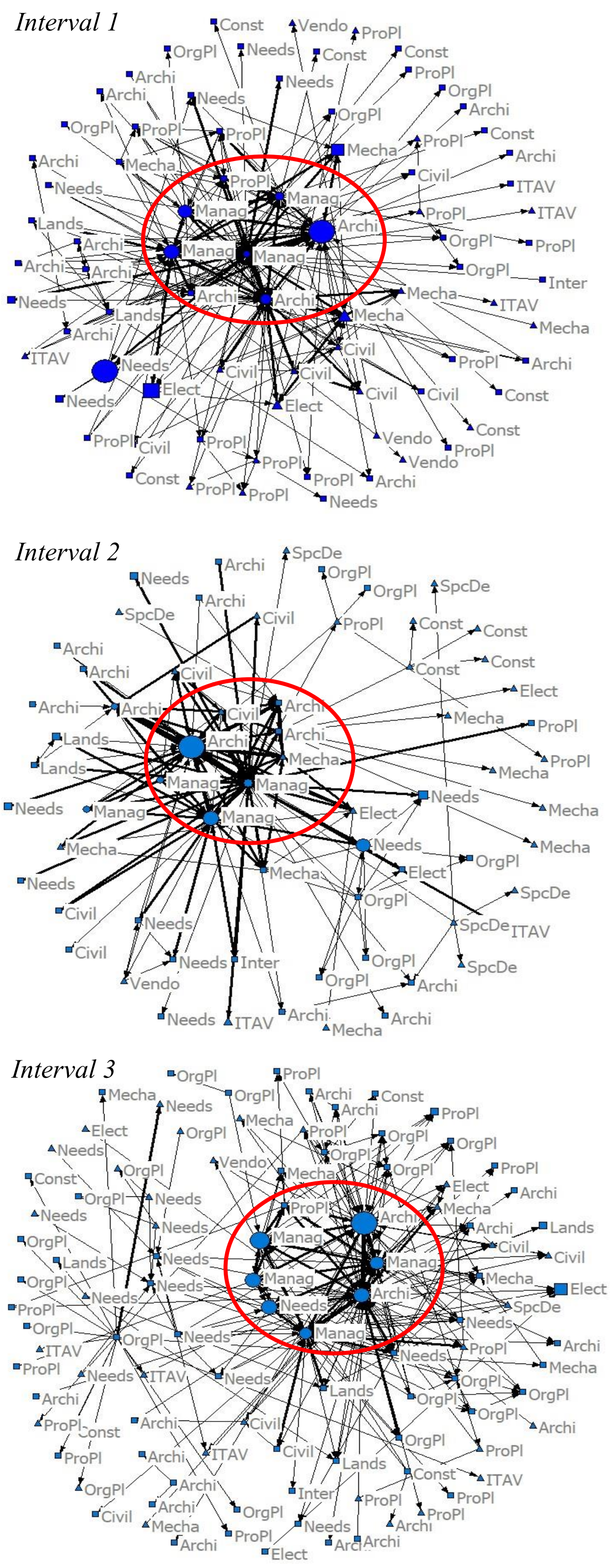


Node colors* show expertise per the first column; ***asterisks* indicate the members that attended project team meetings; ***node sizing*** indicates 'give information' frequency; ***tie strengths*** show the frequency of e-mail exchange between nodes; and ***arrows*** indicate the direction of information exchange.*

Figure 1. Information Sharing Networks During Project's Schematic Design Phase

were not the same members across the time intervals (i.e., four members stayed constant at all intervals). Periphery subnetwork included 71, 57, and 94 members in Intervals 1, 2, and 3 respectively. Of the 179 individuals involved in the project team during schematic design, 39 stayed constant across all time intervals, while others moved in and out of the project team information exchange network.

SNA via UCINET delivered two main observations. First, the core team network displayed a high density (measured as average strength of tie) ranging from 1.41 to 1.53 throughout the three time intervals of schematic design (i.e., overall project network density ranged between 0.036 and 0.067), whereas the density stayed between 0.009 and 0.013 in the peripheral subnetwork. The density of ties from core to peripheral members ranged from 0.15 to 0.22, whereas it fluctuated between 0.12 to 0.15 from periphery to core, meaning that there was a higher information flow from core to peripheral members than the other way around. Overall, core members appeared to finalize key decisions regarding scope, design, budget, and schedule, and transmitting them to the peripheral members to start off their preparations to contribute for later stages of project delivery.



**Red circles show core subnetworks; node shapes –circle, square, triangle– represent Tiers 1,2, and 3 respectively*

Figure 2. Core-Periphery Structured Network During Schematic Design

Second, only in Interval 2 the core included team members from Tiers 1, 2, and 3, and members from areas of expertise such as civil and mechanical engineering in addition to architecture, project management, and project planning. Furthermore, in Interval 2 team productivity was much higher than in Intervals 1 and 3. The case study project team resolved 55% of the project issues during Interval 2 and 15% and 30% of them in Intervals 1 and 3 respectively (Table 1). Therefore, results are consistent with the argument that bringing representatives from Tier 3 into the core team to collaborate with members from Tiers 1 and 2, can help improve team productivity via timely and direct input from key experts to core team in resolving project issues.

In summary, results showed highest team productivity when team members from all tiers and different areas of expertise (e.g., architecture, construction, and mechanical engineering) exchange information following triadic network patterns. UCINET results displayed a dense core subnetwork for information sharing. Team performance was optimal when the core included expertise responding to on-going project needs (e.g., management, architecture, construction, and civil and mechanical engineering) at a given interval. The triadic network patterns identified using Gephi mostly occurred within the core subnetwork. The presence of multiple triadic patterns can ensure high density within the core subnetwork and, therefore, the existence of such subnetwork. Lastly, the members in the core subnetwork also shared information with a peripheral subnetwork where members were loosely connected among themselves.

DISCUSSION

Prior work emphasized the need to increase density of ties within AEC project team networks to improve team performance (e.g., Chinowsly et al., 2008, 2011) and that starting early on during project delivery, cross-functional subteams emerge (Laurent and Leicht, 2019). Our study findings help to further understand how network ties among experts, roles, and tiers are distributed at early stages of project delivery and suggest that AEC project teams naturally form core-periphery networks (Borgatti and Everett, 2000; Lipparini, 2013; Rombach et al., 2017). In such networks, team members in a highly dense core subnetwork might jointly develop information about project program, vision, goals, planning, budget, scope, schedule, and user needs. The composition of the core subnetwork can vary in expertise to adapt to changing project demands and favor team productivity and work plan variability (Al Hattab and Hamzeh, 2018), while participating organizations' networks might display their own patterns depending on their size and structure (e.g., hierarchy, pyramid) (Segarra et al., 2017).

Information diffusion from core to peripheral members can be vital to keep everyone's tasks aligned toward common project goals; therefore, training central members in such information diffusion is vital for project coordination (Hickethier et al., 2013). Aligning with the literature that suggest less than 10 members for AEC project sub-teams (Laurent and Leicht, 2019), our results showed 8 core members (a combination of varying and constant) at all time intervals during schematic design.

Although this study detected a core-periphery network in the case study project, AEC project team networks can display a wide variety of structures for information sharing across project delivery phases. At later stages of design (e.g., design development and construction documents), AEC project networks may consist of multiple dense subnetworks rather than a single dense core subnetwork (Garciacortes, 2017). Subgroups might develop different but interconnected building systems. During construction phases, AEC project networks may heavily adopt hierarchical structures if and when project design is substantially complete and transmitted from project managers to field personnel (Lin, 2014). AEC project team networks for information sharing are dynamic and, therefore, can adapt to varying project demands and conditions.

CONCLUSION

The study's goal was to examine the features of information sharing networks and team performance in AEC projects. Results in our case study showed that AEC project networks can adopt core-periphery structures early in delivery, where members in the core subnetwork diffuse their information to other members in a peripheral subnetwork. Peripheral members are loosely connected, if at all, among them; therefore, their level of involvement in the project is through the core subnetwork and might be comparatively weak. However, they can later become part of the core subnetwork.

The study showed highest productivity when the core subnetwork included members possessing various key expertise areas (e.g., design, construction, and mechanical and civil engineering) from various organizations engaging in multiple triadic information sharing network patterns in email exchange and in project team meetings.

Observation of core-periphery networks in this study coupled with the literature findings suggest that AEC project networks are dynamic and evolve during project delivery. It is, therefore, important to observe them longitudinally to fully understand the project networks phenomenon. From practical perspective, core subnetworks found via social network analyses should inform AEC project team information management and coordination during project delivery. Core subnetworks should be limited to less than 10 members, always stay dynamic in terms of the composure of necessary expertise for given project episodes and reaching out to necessary experts across organizations. Core team members should also be provided coordination training as they are key in keeping peripheral members connected and involved in a timely manner.

The main limitation is that study's findings were drawn from a single case study and only during schematic design phase. Additionally, the study considered only primary expertise areas for team members. Future research should examine information sharing networks across multiple AEC project teams implementing different project delivery methods in addition to owner types and organizational hierarchy as they can influence the formation and evolution of information sharing networks.

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