Network Topologies and Team Performance: A Comparative Study of AEC Projects

Meltem Duva[1]; Sinem Mollaoglu, Ph.D.[2]; Dong Zhao, Ph.D., M.ASCE[3]; and Kenneth A. Frank, Ph.D.[4]

[1]School of Planning, Design, and Construction, Michigan State Univ., East Lansing, MI. Email: duvamelt@msu.edu
[2]School of Planning, Design, and Construction, Michigan State Univ., East Lansing, MI. Email: sinemm@msu.edu
[3]School of Planning, Design, and Construction, Dept. of Civil and Environmental Engineering, Michigan State Univ., East Lansing, MI. Email: dzhao@msu.edu
[4]College of Education, Michigan State Univ., East Lansing, MI. Email: kenfrank@msu.edu

ABSTRACT

The inherent characteristics of the Architectural, Engineering, and Construction (AEC) industry require experts from various organizations and disciplines to collaborate toward shared project goals. However, it is significantly difficult to connect individuals from diverse disciplines, backgrounds, organizations, and effectively integrate their knowledge. Social network approach addresses integration and know-how flow dynamics. However, there is a knowledge gap regarding how network topologies (i.e., parameters relating to nodes, ties, boundaries, and their placements across network) help improve knowledge transfers and optimize project outcomes. Thus, this study compares the network topologies of two similar AEC project teams. We collected e-mail exchange, observational, and archival data and conducted surveys from two projects during the construction phase and performed mixed methods of analysis. The study findings showed different network topologies between the two projects and one of the project networks evolved based on the project needs which yielded better performance. The results suggest that network parameters are not meaningful alone and engagement and network topology matter in measuring AEC project team performance. The results shed light on dynamic and multidimensional characteristics of knowledge transfer networks in complex project teams and contribute to the body of knowledge by providing a methodology in studying project teams in this light.

INTRODUCTION

Architectural, Engineering, and Construction (AEC) projects are inherently unique. Experts from different organizations and backgrounds assemble temporarily to pursue project goals. Transient and dynamic nature of AEC projects presents complexities for experts to effectively integrate their unique knowledge and skills (Korkmaz and Singh 2012) and creates barriers for effective integration. For many years, practitioners and researchers search for systematic ways of dealing with fragmentation problems (Garcia et al. 2020).

Network approach has been adopted by the AEC industry to improve collaboration and integration in complex project teams. Social Network Analysis (SNA) is a tool to visually depict and mathematically assess the interaction patterns between team members (Hanneman and Riddle 2005). The topologies of collaboration networks can provide insights about emergence and evolution of teams and team performance (Lin 2015), individuals' influence and impact over the network (Frank and Fahrbach 1999; Kereri and Harper 2019) and expertise flows occurring to create collective outputs and complete tasks (Chinowsky et al. 2008). SNA helps diagnose problems in collaboration networks and provide remedies at critical points to enhance project performance by using network interventions (Cross et al. 2002). However, it is unknown what network characteristics are favorable for AEC project outcomes, how the project networks evolve during delivery, and how expertise flows through networks.

Therefore, the goal of this study is to identify the network characteristics that impact and enhance team performance in AEC projects. This study examines and compares the network topologies of two similar AEC project teams along with the team performance. We longitudinally collected project e-mail exchange, observational and archival data during the construction phase and performed SNA and evaluated the findings in the light of survey data.

LITERATURE REVIEW

Every AEC project starts with the formation of a new team to achieve the project goals and it is a challenge to unite the diverse group of people with little to no previous experience into a productive team. Experts need to collectively integrate their unique knowledge and complementary skills for optimizing collective output (Chinowsky et al. 2008; Zhao et al. 2021). However, it is significantly difficult to connect individuals from diverse disciplines, backgrounds, organizations and effectively integrate their knowledge and the AEC industry is seeking ways of overcoming the fragmentation problems (Garcia et al. 2020).

Since the development of the concept in 1934 by Moreno, SNA has been used to understand integration and expertise flow dynamics in networks (Moreno 1960). Expertise indicates the knowledge and practical skills required to solve the project tasks efficiently (Frank et al. 2015; Poleacovschi and Javernick-Will 2017). When individuals in the networks do not have the expertise required for a specific situation, they search for it within their networks (Poleacovschi and Javernick-Will 2017) as the people whom individuals connect determine the knowledge they have (Frank and Fahrbach 1999; Valente 2012).

Project networks sheds light on the interaction patterns and expertise flows occurring between team members. AEC project networks consist of project team members and ties between the members representing the interactions between them. Network topology indicates the patterns and arrangement of network members (i.e., parameters relating to nodes, ties, boundaries, and their placements across the network) and is important to understand the functions of a communication network (Kereri and Harper 2019; Zhao et al. 2021). Besides network parameters (i.e., degree, density, centrality) to evaluate properties of a network, understanding the topology of interactions between network components is also important (Albert and Barabási 2002; Duva et al. 2020).

The network parameters were often examined by researchers in the AEC industry. Network density is an important network parameter impacting collaboration and performance. Even though higher network density can foster changes of knowledge transfers, it might increase redundancies and reduce the absorptive capacity (Schröpfer et al. 2017). Therefore, higher network density may not positively impact the performance of a team (Duva et al. 2020) and the density of ties may not need to be evenly distributed within AEC project team networks (Garcia et al. 2020). Castillo et al. (2018) found high connectedness improves performance in case the members are evenly connected, and excessive centralized leadership is avoided (Castillo et al. 2018). Du et al. (2020) presented that shorter average path length and higher clustering coefficients between the nodes fastens the information exchange and stimulates more efficient collaboration.

Previous research has not focused on holistically evaluating the network topologies. Investigating the characteristics relating to nodes, ties, boundaries, and the way nodes are placed and interrelated is important while evaluating the expertise flows. Expertise diversity in networks might foster problem solving and missing necessary expertise in a network might adversely impact outcomes even if they have desirable parameters (Henry and Vollan 2014). Similarly, boundary spanners are important facilitators of knowledge exchange interactions among team members in networks (Iorio et al. 2012) and have a positive effect on team performance (Marco et al. 2010).

Even though there are substantial accepted opinions about how a good network looks and functions, the impact of the structural properties on outcomes depends on the network resources flowing in the network, context, and priorities (Garcia et al. 2021; Henry and Vollan 2014). Therefore, there is a need for holistic evaluations of complex AEC project networks by using longitudinal and in-depth reviews of network topology. We contribute to the literature by holistically assessing complex interdisciplinary and inter-organizational project team, especially in the AEC industry where the conditions and responsibilities are blurry and changing (Cross et al. 2002). Therefore, our research question is as follows:

How does network topology impact expertise flows and team performance in AEC projects?

METHODS

Data Collection

In the pursuit of the study aim, we collected data from two mid-size institutional major renovation projects delivered via Construction Management at Risk. Both projects approximately lasted 2 years and located in the United States. First project had a $18 million budget, and the second project had a budget of $20 million. This paper focuses on the construction phases of the case study projects and longitudinally evaluates and compares the evolution of project networks in the light of team performance. The construction phase of the first project lasted 13 months, while it took 16 months for the second project. We longitudinally collected archival, email, observational and survey data and used SNA to visualize project networks. We also conducted interviews and verified that sociograms developed via email data are representative of their project related communication.

Archival data: We collected project meeting minutes and data from online document sharing platforms. Archival data helped determine start and end dates of phases that the projects were going through (e.g., construction) across the delivery and provided a frame for data analysis.

Email data: Email data were collected with the help of owner's IT department and consisted of email headers (i.e., sender, receiver, time, and subject) of project participants. Non-relevant emails were ruled out based on the senders, receivers and email subject line. Email data are often used to model project team networks and represent team interactions (Franz et al. 2018).

Observational data: Two coders from our research team attended the weekly project meetings and systematically collected observational data (i.e., 112 meetings in total for both projects). Coders recorded the number of "information given" by each meeting attendee (Frank and Zhao 2005) and this number was used to size the nodes in sociograms. The nodes, who gave more information during the meetings were shown bigger in the sociograms. To ensure reliability, the team doublechecked their coding after the meetings and calculated Spearman rank correlation.

Survey data: Project team members were asked to fill out surveys two times during the construction phase and evaluated the performance of their team. A pilot survey was conducted to improve the research quality.

Data Analysis

We drew sociograms by using email exchange data in Gephi. Thickness of the ties (relationships) between nodes (individuals) reflected the strength of relationships, where we assigned 3, 2, and 1 as weights for daily, weekly, monthly communication, respectively. We grouped team members according to: (1) their main roles in the project (i.e., owner, designer, contractor); (2) tiers of hierarchy and operation (Mollaoglu-Korkmaz et al. 2014) and (3) expertise areas such as management, architectural design, project needs and program, civil engineering, mechanical, electrical (Garcia et al. 2020). The nodes were colored based on their expertise area. Observational data were used as a node attribute, where the individuals who gave more information during weekly project team meetings were represented with a bigger dot in the sociograms.

The research team drew the sociograms for whole construction phase, for the time interval until the first survey and for the time interval until the second survey. Sociograms were evaluated longitudinally for each project in the light of the survey results.

RESULTS

Figure 1 below shows the timeline of the case study projects. The construction phase of the first project started in December 2018 and run until January 2020 (13 months). Second project's construction phase started in July 2019 and ended in December 2020 (16 months).

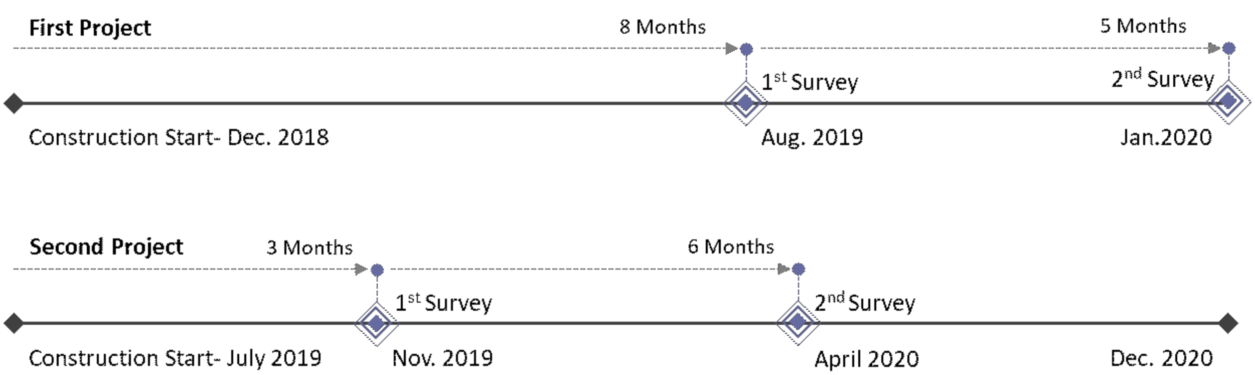

Figure 1. Construction Phase Timelines for Case Study Projects

Throughout the construction phase, the research team conducted 2 surveys (Time 1 and Time 2 hereafter) for each project and measured the team performance based on the evaluation of the team members. ***Figure 1*** depicts the sociograms produced with Gephi and arranged based on individuals' attributes (i.e., role, tier, expertise areas).

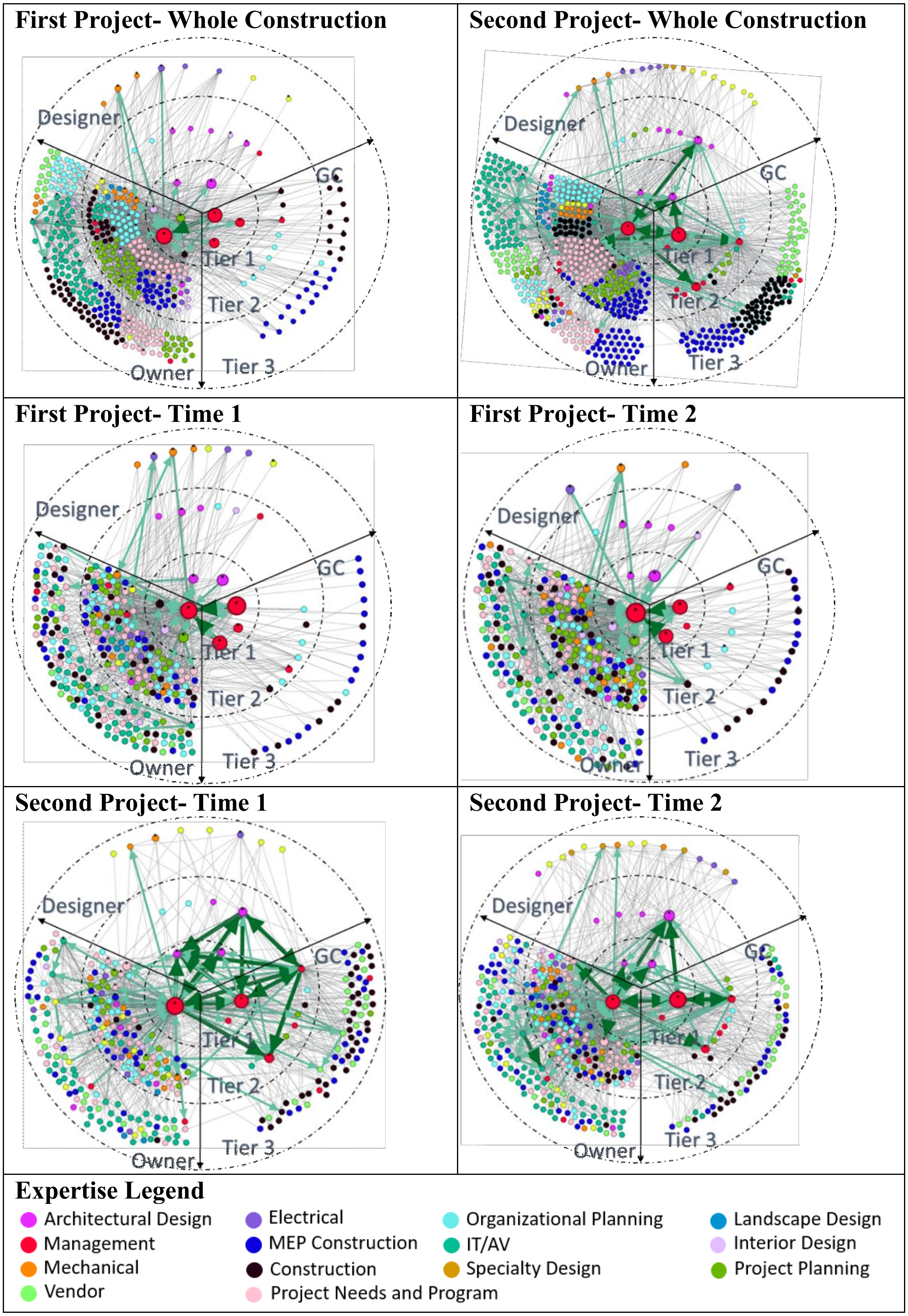

Figure 2. Network Topologies During Projects' Construction Phase

The visual observations of the sociograms showed that expertise flows between different roles mostly took place within Tier 1 in the first project's network. Members in Tiers 2 and 3 of the first project communicated with each other less when they are from different roles and the number of boundary spanning ties across roles were higher in the second project's network. Also, more individuals from designer and GC involved in the second project's network due to the project needs and requirements. The strongest ties (i.e., representing daily communication) were observed only within Tier 1 of the first project team, information leaders emerged in Tier 2 of the designer and GC of the second team, and they were highly effective in knowledge sharing and collaboration.

Moreover, second project's network evolved from time 1 to 2, while the first one remained almost the same. Some observations included: (1) Tier 2 individuals with the strongest connections at time 1 in Designer and GC pie made new connections and distributed some of their loads within the network at Time 2. Similarly, owner Tier 1 individual gained two strongest connections with the individuals from owner Tier 2 that were not present at time 1. (2) Owner Tier 3 individuals' engagement was higher within and across tiers in second project's network. Dynamic and evolving characteristics of the network and bringing in the novel expertise of Tier 3 experts could have helped improve team collaboration and performance for the second project.

Comparison of the two networks and survey results delivered the results as seen in ***Table 1*** and ***Figure 3***.

Table 1. Network Parameters and Topology Features

Network Parameters and Topology Features	**First Project**			**Second Project**		
	Whole	Time 1	Time 2	Whole	Time 1	Time 2
Density	0.01	0.011	0.013	0.008	0.01	0.012
Clustering Coefficient	0.381	0.315	0.375	0.419	0.354	0.443
Average W. Degree	4.416	3.639	4.106	4.848	3.355	4.605
Average Path Length	2.873	2.883	3.073	2.688	2.703	2.72
Exposure	1988	1208	1246	2957	1030	1729
Nr. of Boundary Spanning Ties	1622	974	1005	2286	787	1265
Nr. of All Ties	1958	1179	1203	2879	945	1631
Information Given	6609	3628	2981	4482	1159	1822
Number of Experts	452	332	303	610	307	375
Team Performance		**3.29**	**3.19**		**3.21**	**3.58**

(1) From time 1 to time 2, (a) while the first team showed a slight regress, the second team showed an improvement in all of the network parameters. (b) Especially the number of boundary spanning and total ties showed larger improvement in comparison to the other team and all other network parameters. (2) In the network of first team, (a) the average path length slightly increased indicating that efficiency of expertise flows decreased. (b) The number of experts involved in the networks and number of information given during the face-to-face meetings declined that might have impacted team performance negatively. For both projects, the network densities were not high indicating small percentage of possible ties existed.

Figure 4 below shows the contribution of different tiers in network topology in Time 1 and Time 2. It is observed that Tier 2 and Tier 3 contributed to the expertise flows relatively more in the second project's network. For example, for both time points, Tier 1 members of the first project have given approximately 85% of the total information during the face-to-face meetings, whereas this number was about 60% in the second project. Similarly, more Tier 3 members representing different organizations involved in the networks of the second project. Therefore, results are parallel with the findings that bringing timely and novel expertise from Tiers 2 and 3 can help enhance team performance.

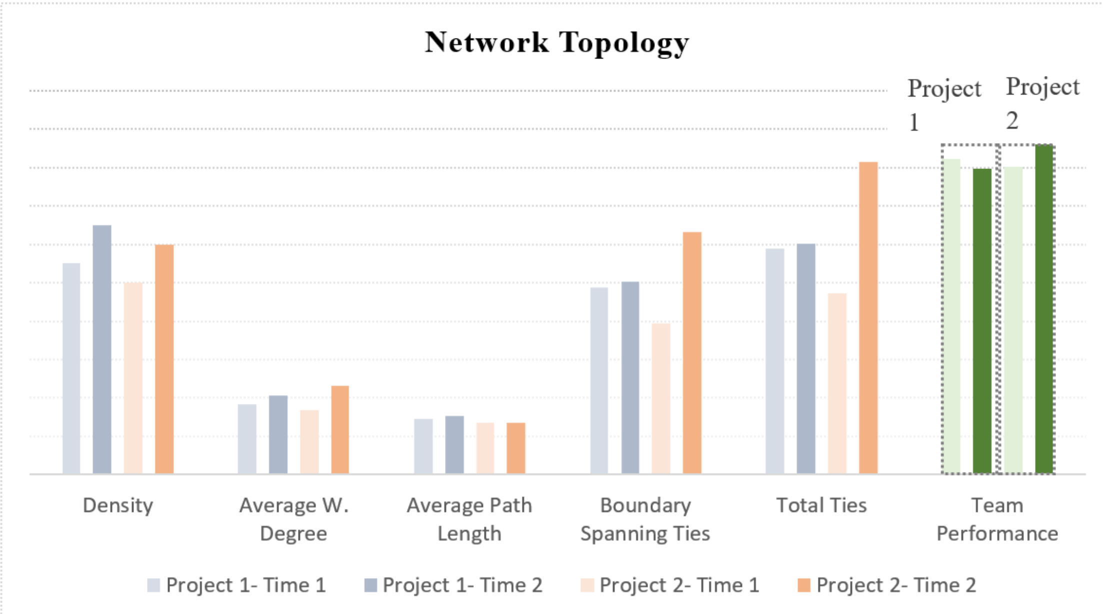

Figure 3. Comparison of Network Parameters and Topology Features

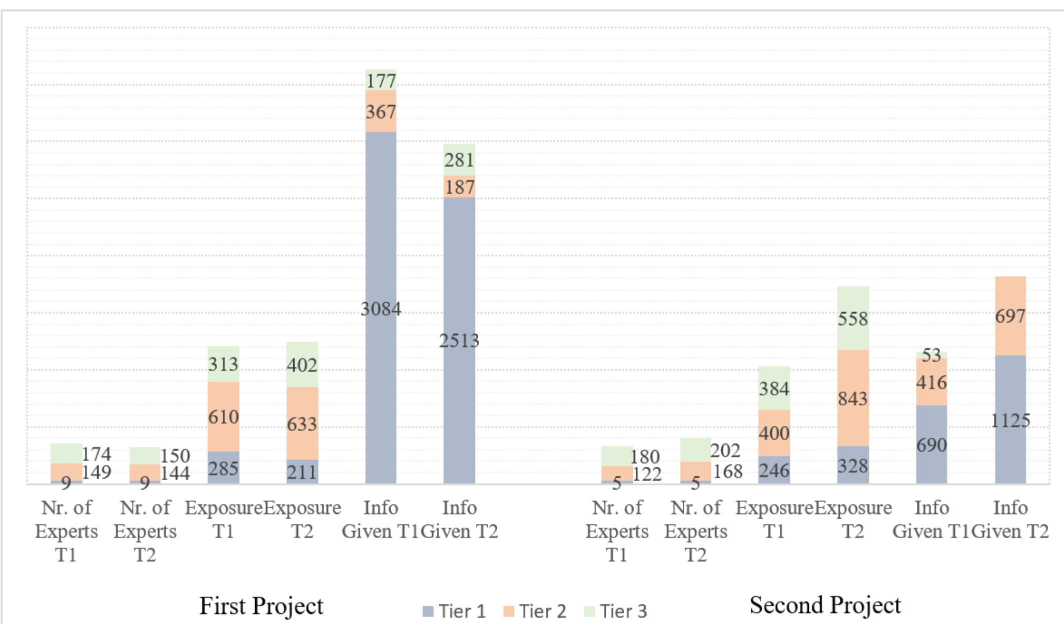

Figure 4. Contributions of Different Tiers in the Network Topology in Time 1 and Time 2

In summary, results showed that two different projects had different network topologies and adopted different expertise flow patterns. The first project network remained the same throughout the project delivery whilst the second project's network evolved based on the project needs and improved the network parameters that enhanced performance. The Tier 1 individuals working for the first project dominated the network and face-to face team meetings, whereas the individuals from Tier 2 emerged as information leaders and enabling enhanced collaboration in the project network and team meetings.

DISCUSSION

This study confirmed that focusing solely on the network parameters without examining the context does not reflect the needs and expertise flows happening in a complex project team network (Duva et al. 2020). Prior work highlighted that dense AEC project team networks improve team performance by enhancing integration (Chinowsky et al. 2008). However, our findings suggest that two networks with similar density had different network topologies and performance levels. The impact of the structural network properties on outcomes depends on the expertise flowing in the network, context and individuals' attributes (Henry and Vollan 2014; Schröpfer et al. 2017). Second, information leaders in Tier 2 supports collaboration and improve expertise flows upwards and downwards. These individuals balance the excessive centrality and communication overload of the hierarchical leaders and contributes to the project success (Castillo et al. 2018). They can help enhance team performance by bringing punctual and novel input from key experts in Tier 3, who are not intensely connected to the project team (Garcia et al. 2020). Third, identifying and including experts from Tier 3 in face-to-face team meetings when necessary, improves their contribution and sensitivity towards the project, help things move and therefore, enhance team performance (Granovetter 1973).

Overall, our findings recommend that project team networks adopt different network topologies based on the changing needs and project context. The most important finding applicable to any project is that focusing solely on network parameters is not enough for advanced team performance as network parameters might not necessarily reflect or fulfill the needs of the complex project networks and engagement and network topology also matter (Boccaletti et al. 2006). Holistic and longitudinal evaluations network topologies would yield to a better understanding of dynamical and mechanical drivers (Chinowsky et al. 2008). Therefore, project managers should stay active and oversee the integration of necessary expertise via different communication media.

CONCLUSION

The goal of this study is to identify the network characteristics that impact and enhance team performance in AEC projects. Our findings show that not only network parameters but also the evaluation of whole network topology is important to understand expertise flows and its effect on the project outcomes. We observed better productivity when networks included members from different key expertise areas and tiers and organizational roles sharing information via email and in the face-to-face meetings. The results showed that two different projects had different network topologies and adopted different knowledge sharing patterns. The first project network remained the same throughout the project delivery whilst the second project's network evolved based on the project needs impacting the performance positively. The Tier 1 individuals working for the first project dominated the network and face-to face team meetings, whereas the individuals from

Tier 2 emerged as information leaders and enabling enhanced collaboration in the project network and team meetings. Information leaders improved the collaboration and dissemination of the necessary expertise.

Lessons learned of this study suggest that holistic and longitudinal evaluations network topologies would yield to a better understanding of dynamical and mechanical drivers. From a practical standpoint, project managers should be adaptive in communications to ensure that relevant experts are engaged regardless of their role, organization, and assignments.

The limitation is that study's findings were drawn from two case study projects during construction phase. Future research should examine expertise flows and network topologies throughout the whole project delivery and with teams using different project delivery methods as contract types, communication protocols and individual characteristics might affect the communication patterns.

ACKNOWLEDGEMENTS

This research was supported by the National Science Foundation through Grant No. 1825678. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the researchers and do not necessarily reflect the views of the NSF.

REFERENCES

Albert, R., and Barabási, A.-L. (2002). "Statistical mechanics of complex networks." *Reviews of Modern Physics*, 74(1), 47-97.

Boccaletti, S., Latora, V., Moreno, Y., Chavez, M., and Hwang, D. U. (2006). "Complex networks: Structure and dynamics." *Physics Reports*, 424(4), 175-308.

Castillo, T., Alarcón, L. F., and Salvatierra, J. L. (2018). "Effects of Last Planner System Practices on Social Networks and the Performance of Construction Projects." *Journal of Construction Engineering and Management*, 144(3), 04017120.

Chinowsky, P., Diekmann, J., and Galotti, V. (2008). "Social network model of construction." *Journal of construction engineering and management*, 134(10), 804-812.

Cross, R., Borgatti, S., and Parker, A. (2002). "Making invisible work visible: Using social network analysis to support strategic collaboration." *California Management Review*, 44, 25-46.

Du, J., Zhao, D., Issa, R. R. A., and Singh, N. (2020). "BIM for improved project communication networks: Empirical evidence from email logs." *Journal of Computing in Civil Engineering*, 34(5), 04020027.

Duva, M., Mollaoglu, S., Zhao, D., and Frank, K. (2020). "Expertise flows in AEC projects: An analysis of multi-level teams for sustainability." *Proc., 18th Annual Engineering Project Organization Conference (EPOC)*.

Frank, K. A., and Fahrbach, K. (1999). "Organization culture as a complex system: Balance and information in Models of Influence and Selection." *Organization Science*, 10(3), 253-277.

Frank, K. A., Penuel, W. R., and Krause, A. (2015). "What is a "good" social network for policy implementation? The flow of know-how for organizational change." *Journal of Policy Analysis and Management*, 34(2), 378-402.

Frank, K. A., and Zhao, Y. (2005). "Subgroups as meso-level entities in the social organization of schools." *Social Organization of Schooling, The*, L. V. Hedges, and B. Schneider, eds., Russell Sage Foundation, 200-224.

Franz, B., Leicht, R., and Maslak, K. (2018). "Framework for assessing resilience in the communication networks of AEC teams." *The Engineering Project Organization Journal*, 8.
Garcia, A. J., Duva, M., Mollaoglu, S., Zhao, D., Frank, K., and Benitez, J. (2020). "Expertise flows and network structures in AEC project teams." *Proc., Construction Research Congress (CRC)*, ASCE, Tempe, AZ.
Garcia, A. J., Mollaoglu, S., Frank, K. A., Duva, M., and Zhao, D. (2021). "Emergence and evolution of network structures in complex interorganizational project teams." *Journal of Management in Engineering*, 37(5), 04021056.
Granovetter, M. S. (1973). "The strength of weak ties." *American Journal of Sociology*, 78(6), 1360-1380.
Hanneman, R. A., and Riddle, M. (2005). *Introduction to social network methods, (Electronic book)*, University of California, Riverside, CA.
Henry, A. D., and Vollan, B. (2014). "Networks and the challenge of sustainable development." *Annual Review of Environment and Resources*, 39(1), 583-610.
Iorio, J., Taylor, J. E., and Sturts Dossick, C. (2012). "A bridge too far: Examining the impact of facilitators on information transfer in global virtual project networks." *Engineering Project Organization Journal*, 2(4), 188-201.
Kereri, J. O., and Harper, C. M. (2019). "Social Networks and Construction Teams: Literature Review." *Journal of Construction Engineering and Management*, 145(4), 03119001.
Korkmaz, S., and Singh, A. (2012). "Impact of team characteristics in learning sustainable built environment practices." *Journal of professional issues in engineering education and practice*, 138(4), 289-295.
Lin, S.-C. (2015). "An Analysis for Construction Engineering Networks." *Journal of Construction Engineering and Management*, 141(5), 04014096.
Marco, M. K. D., Taylor, J. E., and Alin, P. (2010). "Emergence and role of cultural boundary spanners in global engineering project networks." *Journal of Management in Engineering*, 26(3), 123-132.
Mollaoglu-Korkmaz, S., Miller, V. D., and Sun, W. (2014). "Assessing key dimensions to effective innovation implementation in interorganizational project teams: An Integrated Project Delivery case." *Engineering Project Organization Journal*, 4(1), 17-30.
Moreno, J. L. (1960). *The sociometry reader*, Free Press, New York, NY, US.
Poleacovschi, C., and Javernick-Will, A. (2017). "Who Are the Experts? Assessing Expertise in Construction and Engineering Organizations." *Journal of Construction Engineering and Management*, 143(8), 04017033.
Schröpfer, V., Tah, J., and Kurul, E. (2017). "Mapping the knowledge flow in sustainable construction project teams using social network analysis." *Engineering, Construction and Architectural Management*, 24, 229-259.
Valente, T. (2012). "Network interventions." *Science (New York, N.Y.)*, 337, 49-53.
Zhao, D., Duva, M., Mollaoglu, S., Frank, K., Garcia, A., and Tait, J. (2021). "Integrative collaboration in fragmented project organizations: Network perspective." *Journal of Construction Engineering and Management*, 147(10), 04021115.
Zhao, D., Simmons, D., and Chen, Z. (2021). "Interconnectivity in collaboration networks impact on member belongingness." *Journal of Construction Engineering and Management*, 147(8), 04021078.