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Social network analysis for construction crews

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ABSTRACT
Construction crews usually have to share the limited working space with each other during construction to perform their tasks, which increases the chance of interference/conflict and productivity lost. Social network analysis (SNA) has been known as a methodology to determine the conditions of social structures by investigating the interdependencies among a set of actors. The impact of jobsite social network on the performance of the crews has not been well documented in previous research. This research proposes an analytical approach by combining SNA and work plan variation analysis to (1) quantify the influence construction crews receive from jobsite social network, and (2) explore the impact of jobsite social network on the crews' performance particularly on their work plan variation through a case study. The results indicated that there is a positive monotonic association between each of the centrality indices (representing network influence on each crew) and each of the work plan variability indices (representing crew's performance). The more influences a crew receives form the network, the more work plan variation it will have. A better understanding of the existing jobsite interdependencies will help project managers to control it through better planning and leadership, consequently increasing jobsite productivity.

KEYWORDS
Social network analysis; construction crews; centrality; variations; interdependency; work plan; construction management; productivity

Introduction

In the complicated environment of construction projects, where there exist series of interdependent tasks and large number of internal and external uncertainties, one challenge to project managers is how to deal with scheduling and sequencing the large number of specialty trades involved with a project (Tavistock 1966; Pryke 2012; Wambeke et al. 2012). In large building construction projects, delivery is usually handled by numerous subcontractors (specialty trades) with different task packages. Crews usually have to share the limited working space with each other during construction to perform their tasks. When two or more crews are supposed to work in the same working area at the same time, there would be a potential of being influenced by each other (due to inadequate working spaces or work area access, overcrowded jobsite, prerequisite work, availability of labours, equipment or materials, safety hazards, etc.) and subsequently loosing productivity (Thomas et. al. 2006; Watkins et al. 2009). Studies showed that the same subcontractor crews have better efficiency/productivity (about 30%) on similar scope in areas where only one subcontractor owns the working space (Thomas et al. 2006; Seppänen 2009).

Social network analysis (SNA), introduced by Moreno (1960), has been known as a methodology to determine the conditions of social structures by investigating the relations and interrelationships of a set of actors (De Nooy et al. 2005). Plausibly and arguably, subcontractor crews and their spatial relationships in a construction project constitute a kind of social network (called jobsite social network in this paper), which can be analysed via SNA. In the jobsite social network, where the main focus is on the physical relationships, two crews are connected if they share the working area in a time period of the project. Most of the social network studies conducted in the project management research have identified the social network based on communication and information flow among the project teams (for example, see Chinowsky et al. 2008). Research pertaining to the jobsite social network is very limited. Wambeke et al. (2012) outlined a procedure to identify the jobsite social network. Abbasian-Hosseini et al. (2014) identified the benchmarks for the inefficient trades in a construction project using jobsite SNA. Wambeke et al. (2014) created a decision-making system by coupling the variation analysis with the associated social network of trades to target trades in an effort to reduce variation. In the previous studies related to the jobsite social networks, the

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impact of jobsite social network on the crews' performance has not been documented. Furthermore, in the previous studies, due to the research objectives, relationships among the crews for the whole of the project have been shown by a single social network. Since the relationships change over the course of the project, another way to analyse the jobsite social network is to consider the variation of the network topology over the time. Thus, the construction industry has lacked a systematic and applicable approach to quantify the impact of jobsite social network on the crews and track its variation over the course of the project. The research objectives are to (1) propose an analytical approach based on SNA to quantify the influence working crews receive from jobsite social network at any time of the project, and (2) explore the impact of jobsite social network on the crews' performance particularly on their work plan variation through a case study. The research contributes to the body of knowledge as it first examines the jobsite social network from a different standpoint of view (dynamic view); second, uses SNA to quantitatively estimate the potential of conflicts among the crews; and third, demonstrates the impact of network on the crews in a case project by evaluating the consistency between the centrality of the crews in the network and their work plan variation in the project.

The proposed approach will help construction managers and superintendents to visualize and the spatial relationships of crews and quantify the potential of conflict over the course of a project. Specifically, it helps them to identify (1) the crews that are more under the influence of the jobsite social network than the others and (2) the time periods with the most severe conflict potentials; so they can focus managerial efforts (both before and after start of the project) on them.

Research background

SNA in construction-team communication and information exchange

SNA, introduced by Moreno (1960), examines structures of human groups, communities or a society by investigating the interactions, relations and interrelationships of a set of actors (nodes) (De Nooy et al. 2005; Park et al. 2011). A network consists of a set of ties (represents relationships) that exist among different nodes (represents actors). SNA has been applied to many research fields (such as aerospace, automotive bodies and computer science) with the goal of investigating various relationships among organizations and individuals, while classic SNA research has concentrated on sociological networks (Park et al. 2011).

Construction engineering and management researchers gradually turn to the social sciences for the interpretation of issues related to construction (Chinowsky et al. 2008; Pryke et al. 2011). Formation of networks in construction can facilitate project team operation and improve communication, which results in solving the problems of fragmentation. With SNA, construction management teams can map communication and identify information sharing problems in construction projects. Researchers started exploring the important capabilities of social network theories in construction management (Malisiovas and Song 2014). The SNA applications are diverse, but mostly focused on the project team communication and information exchange. Chinowsky et al. (2008) attempted to reduce the uncertainty during construction by network modelling of the information passed through the team members. Chinowsky et al. (2010), through some case studies, demonstrated the need to introduce the social network model into project organization development. Chinowsky et al. (2011) used SNA to assess project effectiveness by focusing on the alignment of actual stakeholder knowledge exchange with knowledge exchange requirements defined by task relationships. Park et al. (2011) investigated the formation and impact of construction firms' collaborative networks for performing international projects, using an SNA approach.

SNA has also been used in other areas such as performance measurement and safety. Dogan et al. (2013) attempted to assess the coordination performance of a construction project based on the centrality measures of e-mail communication network. Keung and Shen (2013) used statistical techniques to measure the contractor's networking performance from several aspects such as information exchange, project communication system and knowledge sharing for collaboration. In safety research area, Albert and Hollowell (2014) used SNA to explore the relationship between patterns of worker interaction and situational hazard awareness in construction projects. In another research, Alison and Kaminsky (2017), using SNA, explored how gender impacts work crew safety communication. Furthermore, Pirzadeh and Lingard (2017) used SNA and interviews to evaluate the dynamic aspect of social interactions between project participants as decisions were made related to work health and safety in a construction project.

SNA in construction – social network of construction crews (jobsite social network)

In the jobsite social network, actors are working crews of the project and two crews are connected to each other (have relationship) in the network if they physically work in the same area(s) at the same time of the project. Wambeke et al. (2012) believed that an underlying network of crews exists in a construction project and its recognition can contribute to project success. Understanding the jobsite social network can help the construction site managers to coordinate the crews effectively and succeed in the challenging environment of project; however, achieving this skill takes years of experience and few superintendents could articulate it (Wambeke et al. 2012, 2014). Wambeke et al. (2012) outlined a procedure to identify the organizational social network of construction crews and determine its key members. They provided a detailed description of the steps to create a social network of crews, as well as how to determine the key members of the network using degree and eigenvector centrality. In 2014, Wambeke et al. couple the variation analysis with the associated social network of trades to create a decision-making system. They determined the causes of variation that pose the greatest risk of impacting project performance, then analysed the social network of trades to develop a decision support system to target trades in an effort to reduce variation.

Abbasian-Hosseini et al. (2014) proposed a social-network-based data envelopment analysis (DEA) benchmarking procedure (SDBP), which combines DEA (assessing the relative efficiency of DM units) and SNA to identify the benchmarks for the inefficient specialty trades. Lin (2014) studied the underlying jobsite management problems and potential technology interfaces by analysing jobsite social network and found that the order-management network has the highest degree of social density. Priven and Sacks (2015) explored how Last Planner system strengthens the project social network by building relationships among construction teams. Abbasian-Hosseini et al. (2015, 2017), using jobsite SNA, demonstrated how social conformity, one of the various social influence types that results in a change of performance/behaviour in order to fit in a group, plays a role in the subcontractors' performance particularly in their work plan reliability. Results of their case study showed that a subcontractor's performance, specifically its work plan reliability, is under the influence of its local network.

Gaps in knowledge

The following gaps have been identified in using SNA to resolve the construction-related issues:

(1) Since the basic definition of the term 'relationship' in sociology refers to 'information exchange', most of the previous construction research with regard to social network focused on the information exchange/communication (Thorpe and Meade 2001; Pryke 2004; Hossain 2009). There is also some research focused on the formal (contractual) relationships of the parties in the project (West 2014). The research pertaining to the spatial social network of the crews in the jobsite during construction, as an informal underlying structure of construction project, is very limited. The construction industry lacks an applicable method to quantify the influence of jobsite network on the working crews.
(2) In the previous studies of jobsite social network, all the relationships among the crews over the course of the project have been presented by a single constant social network. However, since the frequency and severity of crews' relationship fluctuate over the course of the project, there is a need to consider the dynamic aspect of the relationships.
(3) The previous research pertaining to the jobsite social network provided decision-making tools to show the usefulness of the SNA application (Wambeke et al. 2014), but the impact(s) of network on the performance of the crews has not been studied. The relationship between the work plan variation of a working crew in the project and its position and situation in the network has not been fully investigated.

This research is important and unique as it fills the aforementioned gaps in the body of knowledge by proposing a systematic and applicable approach that can quantify the influence of jobsite social network on the crews' performance and track its work plan variation over the course of the project.

Methodology

Figure 1 shows the different steps of the methodology to achieve the research objectives. The research uses a case study to show the applicability of the proposed approach.

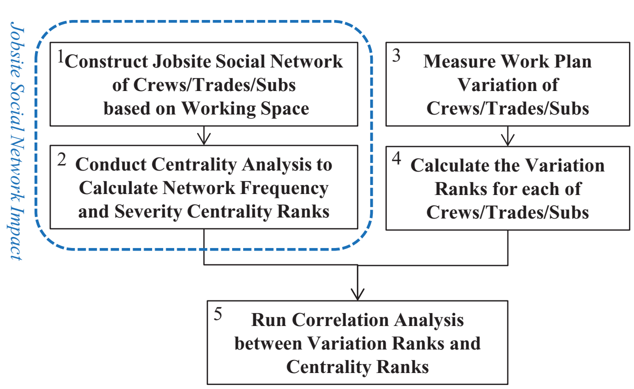


Figure 1. Methodology steps to achieve Research Objective 1.

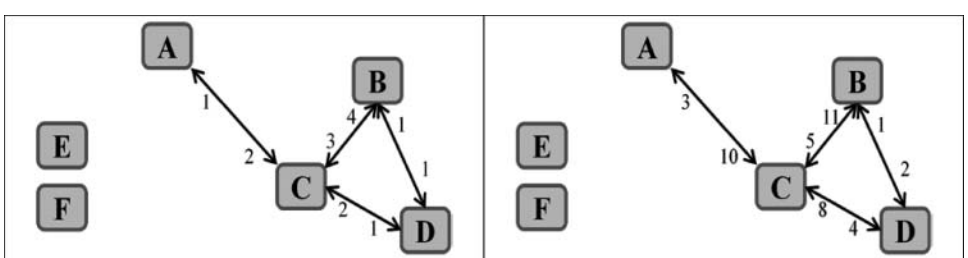
A general contractor (GC) overseeing 43 subcontractor crews, involved with the construction of a 150,000-square-foot data centre participated in the case study. A GC with numerous subcontractor crews was chosen because the research is focused on the social network that exists among the various crews, thus there was a desire for a study a project with more than just a few subcontractors. The \$50M project entailed the build-out of an existing warehouse building into a data centre and white space computer labs. Construction ran from February through September 2010 and the project was studied from the beginning of March through the completion at the end of September. There were nearly 1200 tasks performed by the 43 various crews working on the data centre during the course of this 28-week study. Under the GC's permission and support, the project tracks data on the date and location where each task was performed, which crews worked simultaneously in the same area each week, and the frequency and severity on the starting time and duration variation. The influence from the researchers on the relationship among the crews was minimal because the researchers did not interfere with allocating the trades or tracking the performance directly.

(1) *Construct jobsite social network of subcontractor crews based on working space*: The social networks are constructed based on spatial proximity due to the desire to examine which crews were physically working together in a shared physical space. A social network consists of a set of vertices and ties between them. The crews are defined as the vertices and the ties among them indicate that if they are going to work in the same space at the same time. The required data for constructing a social network is collected and tabulated by an adjacency matrix (A_{SN}). Two subcontractor crews are called adjacent/neighbour if they are connected by a tie in the network. Table 1 shows a schematic $A_{SN} \cdot A_{SN}$ represents the existing relationships, where the elements 'a_{ij}' and 'a_{ji}', called 'line value', indicate how frequent the relationship or how strong the social network tie is between subcontractor crews i and j. A_{SN} can be symmetric ($a_{ij} = a_{ji}$) or asymmetric ($a_{ij} \neq a_{ji}$) depending on the purpose of social network development. In this study, the networks are assumed to be asymmetric, because it is assumed that the influence of crew i on j may not be necessarily as the same as the influence crew j has on i.

Table 1. Schematic adjacency matrix (A_{SN}) for relationships of subcontractor crews.

	Sub 1	Sub 2	…	Sub j	…	Sub n
Sub 1	0	a_{12}	…	a_{1j}	…	a_{1n}
Sub 2	a_{21}	0	…	a_{2j}	…	a_{2n}
…	…	…	…	…	…	…
Sub i	a_{i1}	a_{i2}	…	a_{ij}	…	a_{in}
…	…	…	…	…	…	…
Sub n	a_{n1}	a_{n2}	…	a_{nj}	…	0

In the proposed method, instead of making a single social network for all the existing spatial relationships of the project, several networks are created; each represents the crews' interferences for a time interval. Since the construction managers make their work plan on a weekly basis, a network is made for each week of the project to track the interdependencies with more accuracy. Thus, if two crews are supposed to work in the same working area in a week (even if they work in the same working area for one day in that week), there will be a tie between them in the jobsite social network created for that week. Working in the same area increases the potential of interferences or disruptions (like blocking the access of one crew by another crew). Directed reciprocal lines were used to establish the social networks for the proposed method. Two different networks are created, one based on the 'frequency' and the other based on the 'severity', to accurately estimate the impact of the networks. In the frequency network, the value on the ties (weights) show the number of times each of the crews perform, while in the severity network, the weights indicate the total number of days (the summation of tasks' duration) for each crew. Figure 2 depicts a



a) Frequency network
b) Severity network

Figure 2. Schematic jobsite social network.

schematic example of the jobsite social network. Assuming it has been created based on the work plan of the first week of a project, it shows that four crews (A, B, C and D) out of a total of six crews in the project are going to perform their tasks in the first week of the project. A tie between the two crews shows that they are going to share the working area to perform their tasks at the first week of the project. Figure 2(a) shows the frequency network where the weights indicate the number of tasks each of them performs. For instance, the tie between A and C shows that the Crews A and C perform 1 and 2 tasks, respectively, in the same working area in Week 1. In the severity network (Figure 2(b)), the weights indicate the summation of the tasks' duration. For instance, the '3' and '10' on the tie between A and C show that Crew A's task takes 3 days to complete while the summation of the tasks' duration for the Crew C is 10 days in Week 1. The tie weights represent the magnitude of influence the crews are going to have on each other in that time interval. It should be noted the tasks performed by various crews may not be equal (there may be different operations, and therefore, different equipment, workforces and materials). However, it was assumed all the tasks to have the same magnitude of influence in this method. There are usually some boundaries for construction crews for their task breakdown. For instance, they may break their tasks down into the activities with the maximum duration of one week and the maximum cost of $10,000. These kinds of boundaries/scopes in defining the tasks lighten, if not eliminate, the inequality impacts of the crews' operation. When there are no boundaries/scopes for making work plan, the weights can be adjusted according to the tasks' characteristics to balance the inequality of the crews' operation.

(2) *Conduct centrality analysis to calculate network frequency and severity centrality ranks*: 'Centrality' measures the relative importance of the vertices within a network. There are various ways to measure the centrality such as degree, betweenness and closeness centralities (De Nooy et al. 2005). In this research, *Weighted In-degree Centrality* is used to measure the receiving influences by each crew. Degree centrality of a node in the network is the number of its ties; in-degree centrality is the number of its incoming (receiving) ties (Equation (1)); and the *Weighted In-degree Centrality* is the summation of the weight of its incoming ties (Equation (2)) (Opsahl et al. 2010):

$$C_D^{-}(i) = \sum_{j}^{N} x_{ij}^{-} \tag{1}$$

In Equation (1), $C_D^{-}(i)$ is the node in-degree centrality for a binary network (the strength of all ties is assumed to be equal), i is the focal node, j shows all other nodes, N is the total number of nodes in the network, and x is the adjacency matrix of a binary network (x_{ij}^{-} is 1, if there is a tie from node j to i):

$$C_D^{w-}(i) = \sum_{j}^{N} w_{ij}^{-} \tag{2}$$

In Equation (2), $C_D^{w-}(i)$ is the weighted in-degree centrality for a weighted network, and w is the weighted adjacency matrix (w_{ij}^{-} is greater than 0, if here is a tie from node j to i and the value indicates the tie strength).

The weighted In-degree centrality of a crew represents the frequency and severity of the tasks performed by the other crews (neighbours) in the working area(s) the crew works (i.e. workload in the neighbourhood). It indicates how much influence the crew receives from the network. For the frequency network shown in Figure 2(a), the weighted in-degree value is 2 for Crew A and 4 (=3 + 1) for Crew B. These numbers are 10 and 7 (=5 + 2) for the severity network (Figure 2(b)), respectively.

(3) *Measure work plan variation of subcontractor crews*: Work plan variation (also called variation in this study) is defined as the time difference between what was planned and what occurred. It represents the reliability of a work plan. Variation is one of the root causes of productivity loss (Howell et al. 1993; Ballard et al. 2005; Wambeke et al. 2011; Hajifathalian et al. 2012). Four variables (Equations (3)–(6)) are measured for each of the crews at each week over the course of the project as the indices of work plan variation (showed by '*V*' in the equations). By measuring these four variation variables, the performance level of crews was measured from both variation frequency and severity standpoints:

$$V_1: \text{Start} - \text{time variation frequency} = \frac{\text{Number of tasks not starting ontime}}{\text{Total number of planned task}} \tag{3}$$

$$V_2: \text{Start} - \text{time variation severity} = \frac{\text{Summation of delays in starting the tasks (days)}}{\text{Summation of planned tasks' duration (days)}} \tag{4}$$

$$V_3: \text{Completion} - \text{time variation frequency} = \frac{\text{Number of tasks not finishing ontime}}{\text{Total number of planned task}} \quad (5)$$

$$V_4: \text{Completion} - \text{time variation severity} = \frac{\text{Summation of delays in finishing the tasks (days)}}{\text{Summation ofplanned tasks}' \text{duration (days)}} \quad (6)$$

(4) *Calculate the variation ranks for each of subcontractor crews*: Each subcontractor crew is given a rank based on his/her variation variables' value (totally four ranks based on the four variation variables).

(5) *Run correlation analysis between variation and centrality*: In order to investigate the impact of jobsite social network on the performance of the crews, the consistency, using correlation analysis, between the influences each crew receives from the networks and its work plan variation is evaluated over the course of the project.

Case study results

The case study was a $50M, 150,000-square-foot data centre. Subcontractor crews were supposed to make their work plan based on the master schedule developed by the GC. They had been asked to breakdown their tasks to the activities with the maximum duration of one week and the maximum cost of $10,000. These rules in defining the tasks of the work plan make the crews' work plan variation comparison more reliable. In this section, the application of the proposed approach is explained step by step and the results are discussed.

(1) *Construct jobsite social network of subcontractor crews based on working space*: For each of the 28 weeks of the case study project, two jobsite social networks were developed, one based on the frequency and one based on the severity (overall, 28 × 2 = 56 networks). For instance, the jobsite social networks depicted in Figures 3 and 4 show the interdependencies of the trades from frequency and severity standpoints in the 18th week of the project. Eleven crews were active in Week 18. The existing ties among the crews indicate which crews had to share the space during Week 18. The weights of a tie between two crews indicate the frequency (Figure 3) and severity (Figure 4) of the influences they sent to each other in that time interval. For example, the weights of 2 and 1 for the tie between the 'Ceiling Tile' and 'Painting' crews in the frequency network indicate that the 'Ceiling Tile' and 'Painting' crews performed 2 and 1 tasks, respectively, in the same area in Week 18. These weights are 8 and 1 in the severity network, which shows the influence of the 'Ceiling Tile' on the 'Painting' crew is eight times more when you consider the duration (severity) of the tasks.

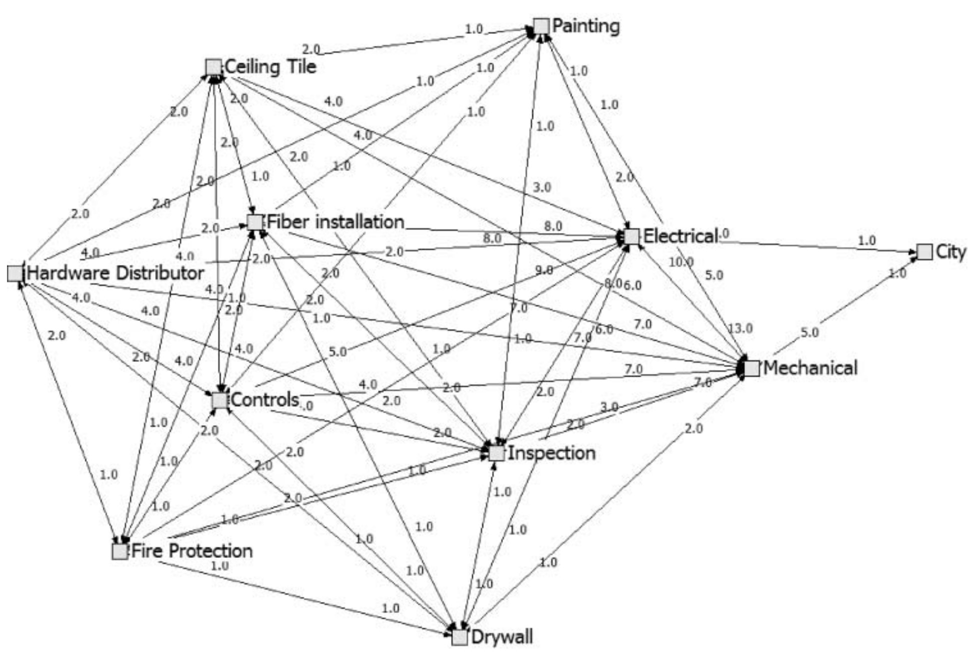


Figure 3. Jobsite social networks in Week 18 based on frequency.

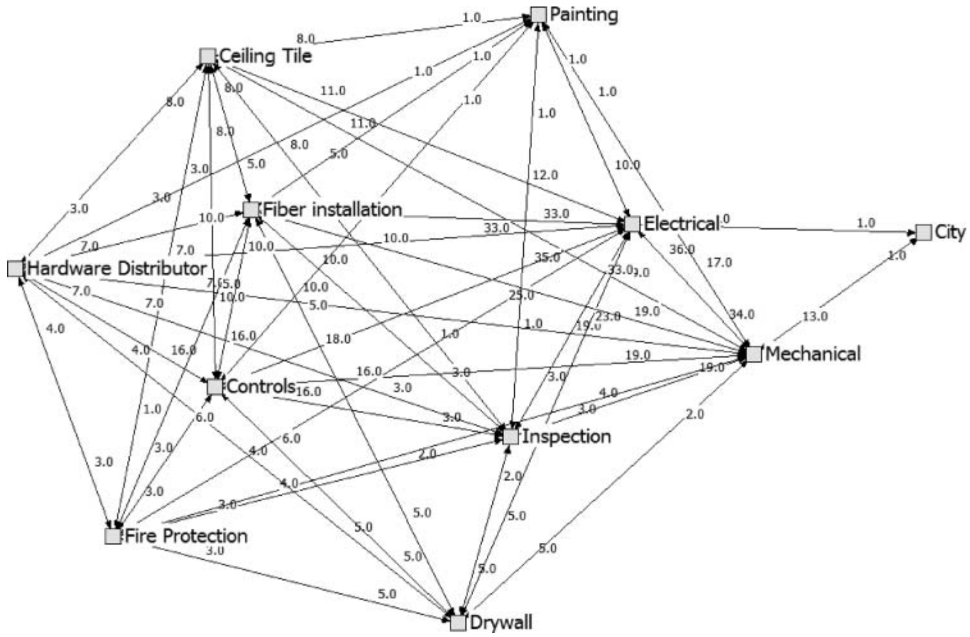


Figure 4. Jobsite social networks in Week 18 based on frequency.

Figure 5 shows all the 28 networks of the project; to make the networks less confusing, the weights have not been shown in the figures. It demonstrates the dynamic aspect of the jobsite social network. It visualizes how the interferences change among the 43 subcontractor crews over the course of the project. There are two facts about the dynamic aspect of jobsite social network can be explained by Figure 5:

(1) The network complexity can be represented by the network density. Network density simply shows how congested a network is. The 'network weighted density', was calculated for each of the network (can be seen under each network), is the ratio of the sum of the weights of ties versus the maximum possible ties in the network (Liu et al. 2009). The network density fluctuates week by week but gradually increases as project proceeds until it reaches its peak in the Month 6 (Weeks 21–24). The density decreases in the last two weeks of the project. This trend reflects the workload of a typical construction project. The workload is low at the beginning and then it increases gradually until a few weeks before the project completion.

(2) The impact of jobsite social network on the crews depends on their position and situation in the network. As the network topology changes in each week, the position and situation of a crew changes. Thus, the influence it receives from the social network varies from one week to another. For instance, two crews ('Electrical' and 'Painting') are highlighted in Figure 5, so their position and situation can be tracked in the networks over the course of the project. The one shown by a rectangular is 'Electrical' crew and the other one indicated by a circle is 'Painting' crew. Painting crew started its work from Month 3 (Week 9), while the Electrical crew performed its tasks from the beginning of the project. As shown, the position of them changes in each week as the topology changes, i.e. they experience a different neighbourhood and different relationships in each week. Thus the network influence on each of them fluctuates over the course of the project. For instance, comparison between the social networks of Weeks 13 and 14 indicates that the Painting crew (highlighted by a circle) gets less influence (i.e. less interferences) from the network of Week 13 than Week 14, while the situation of the Electrical crew (highlighted by a rectangular) remains almost the same.

(3) *Conduct centrality analysis to calculate network frequency and severity centrality ranks*: Centrality analysis was conducted and two centrality values (one based on the frequency and one based on the severity network) were calculated for each crew in each week (based on Equations (1) and (2)). Table 2 shows the centrality analysis results for Week 18 (refer to the jobsite social networks in Week 18 shown in Figures 3 and 4). The second and third columns represent the values of the

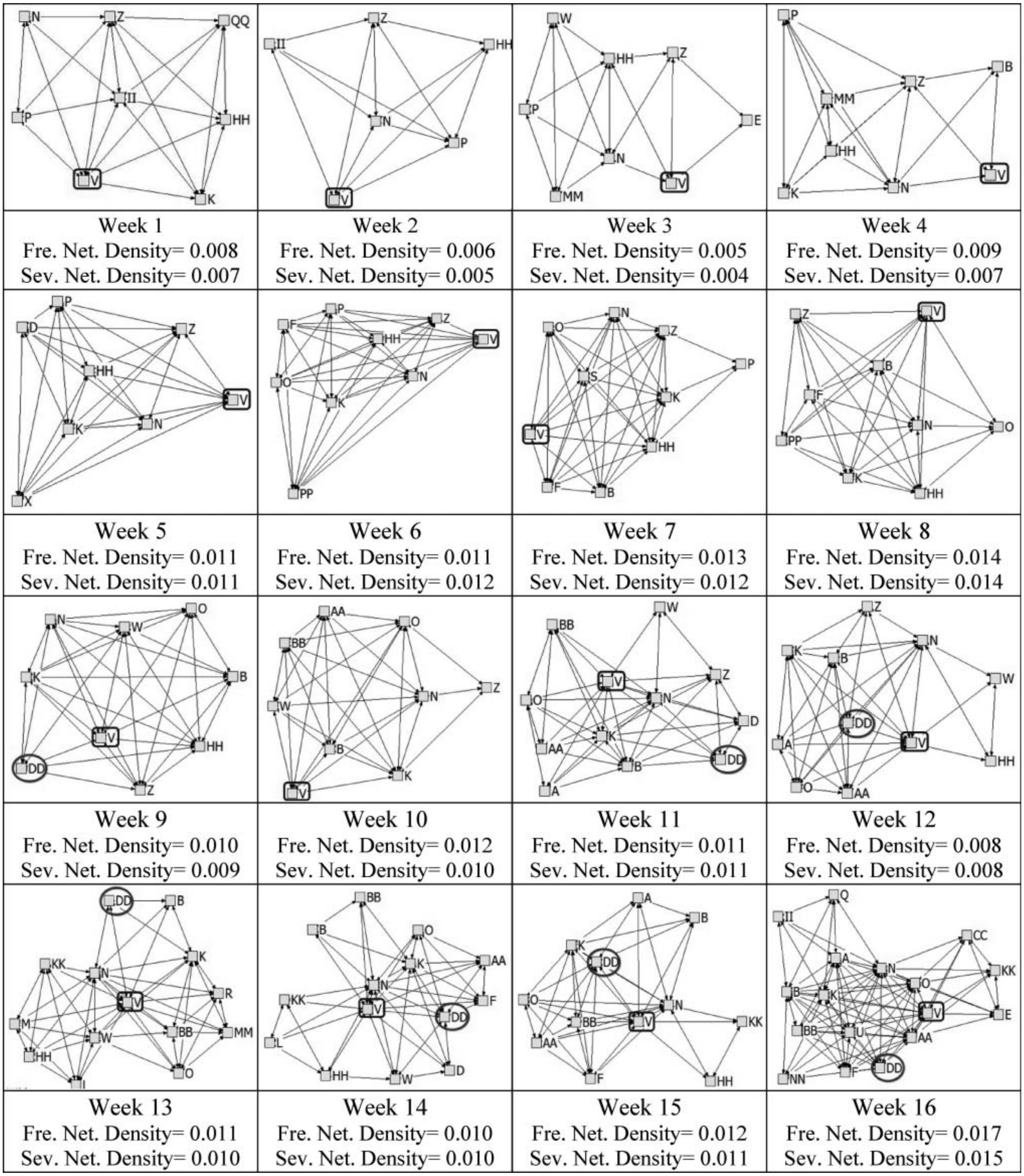


Figure 5. Jobsite social network topology over the course of the project (28 weeks).

Note 1: The node labels used in the drawings represent the trades/subs as follows: A: Ceiling, B: Inspection, C: Door, D: Flooring, E: Water, F: Unistrut Hangers, G: CAT, H, Fire Stopping, I: Ceramic Tile, J: Interior Fixtures, K: Drywall, L: Energy Company, M: City, N: Mechanical, O: Fire Protection, P: Specialty Concrete, Q: Owner, R: Flooring/Finishing, S: Global Inspection, T: Bathroom Fixture, U: Wall Finishing, V: Electrical, W: Roofing, X: Door Supplier, Y: Hardware Distributor, Z: Concrete, AA: Controls, BB: Fiber Installation, CC: Generator, DD: Painting, EE: Electrical Specialty, FF: Floor Cleaner, GG: Security Cage, HH: Steel Fabricator, II: Architect, JJ: Owner/Arch, KK: Substation Install/Testing, LL: Steel Cladding, MM: Misc, NN: Unistruct Installer, OO: Caulking, PP: Fire Proofing, and QQ: Utilities.

Note 2: To make the networks less confusing, the weights have not been shown in the figures, so there was no need to separately show the frequency and severity network.

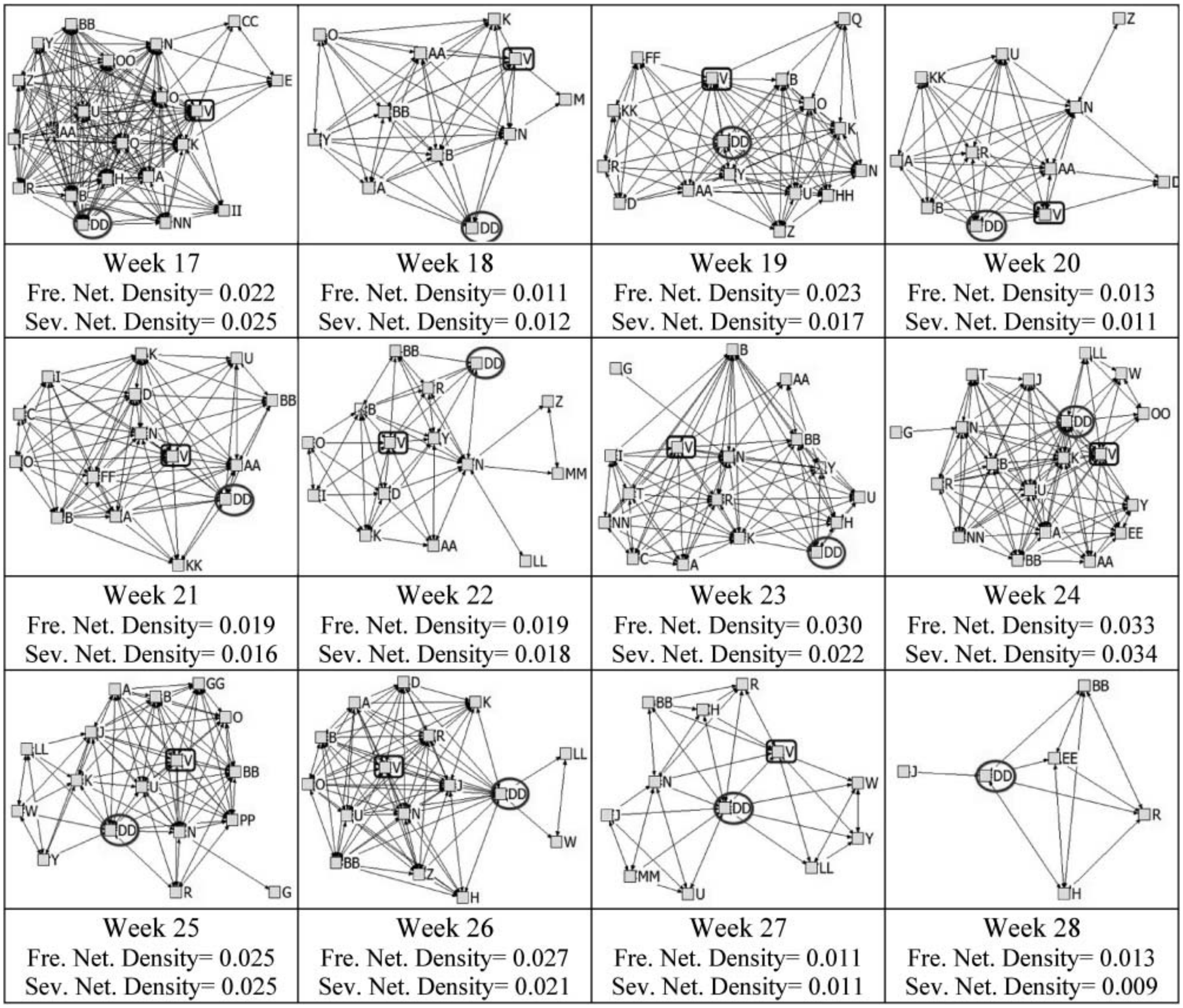


Figure 5. (*Continued*)

weighted in-degree centrality for the frequency and severity network, respectively. The fourth and fifth columns are the ranks of the crews based on their centrality values (called centrality rank (CR)). Results show that the Electrical crew received the most influence from the frequency network, and the 'inspection' and 'Hardware Distribution' crews suffers more than the others from the jobsite social network based on the severity. The centrality values quantify the influences of the jobsite social network on the crews and ranking highlights those crews get more influences from the networks. CRs are measurements that help the project managers and superintendent to identify the crews with high conflict potentials. The crews with high frequency and severity centrality ranks (high FCR and SCR) have probably the higher chance to be impacted by the jobsite interferences. Project management team can work with the site managers or the crew leaders to take proper actions in order to lighten the impacts. One action could be adjusting the planned schedule to decrease the pressure on the high-ranking crews, which could bring additional cost. More discussion will be provided later in this section. The same analysis was done for each of the 28 weeks of the project (overall 28 FCRs and 28 SCRs recorded for each crew).

(4) *Measure work plan variation of subcontractor crews*, & (4) *Calculate the variation ranks for each of subcontractor crews*: The four work plan variation variables (V_1 to V_4, refer to Equations (3)–(6))

Table 2. Centrality analysis results for the jobsite social network in Week 18.

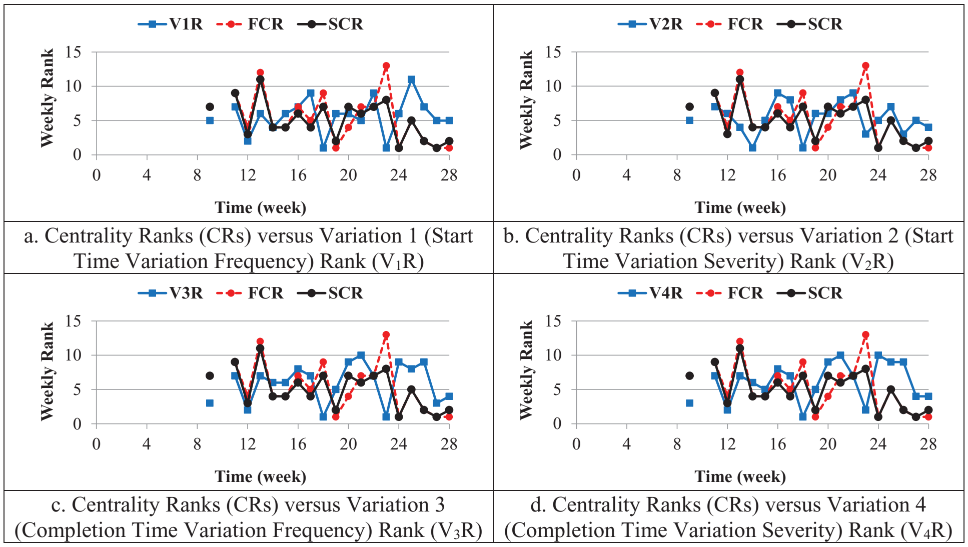
Trade	Weighted In-degree Centrality – Frequency Network	Weighted In-degree Centrality – Severity Network	Frequency Centrality Rank (FCR)	Severity Centrality Rank (SCR)
Electrical	35	94	1	2
Mechanical	31	94	2	2
Inspection	30	102	3	1
Hardware distributor	30	102	3	1
Fibre installation	30	54	3	4
Controls	29	91	4	3
Fire protection	19	54	5	4
Ceiling	17	52	6	5
Drywall	15	45	7	6
Painting	15	54	7	4
City	6	14	8	7

were recorded as performance indices for each crew over the course of the project. The crews were ranked based on their work plan variation variables' value in each week (V_1R, V_2R, V_3R and V_4R, four ranks for each crews in each week refer to the four measured variables). For instance, the work plan variation variable ratios recorded for the crews in Week 18 are shown in Table 3. Column 1 shows the crews performed their tasks in Week 18. Columns 2–7 are the data recorded according to the project work plan and schedule in Week 18. The remaining columns show the work plan variation variables along with their ranks in Week 18.

(5) *Run correlation analysis between variation and centrality*: From the schedule performance control standpoint, the key crews for the project managers to focus on are those with the higher work plan variation, because when one crew experiences variation, other crews can be impacted. From jobsite interference network standpoint, the key crews are those with the higher centrality, because they receive higher impacts from the network. To examine the impact of jobsite social network on the crews' performance, it is tested to reveal how much the network impact is correlated with the crews' work plan variation indices. To do so, the consistency between the CRs (FCR and SCR) and VRs (V_1R, V_2R, V_3R and V_4R) of the crews was measured. Correlation analysis was conducted to quantify the consistency and find out how significant the relation between the CRs and VRs is. Before presenting the correlation analysis results, to have a better understanding of the relation, the consistency between the CRs and VRs has been depicted for two of the crews, 'Painting' and 'Electrical', in Figures 6–9 (Figures 6 and 8 are for 'Painting', and Figures 7 and 9 are for 'Electrical' crew). They show how the VRs change when the CRs of the crews change over the course of the project. Figures 6 and 7 show the consistency week by week, while month-to-month consistency has been depicted in Figures 8 and 9. Painting crew started its work on Week 11, while Electrical crew performed tasks from the beginning to the end of the project. A sensible consistency between the weekly CRs and VRs can be inferred for the 'Painting' crew based on the charts of Figure 6. The relation between the CRs and each of the VRs became more noticeable when their consistency was

Table 3. Work plan variation analysis results for the Week 18.

Trade	# planned tasks	Total planned tasks' duration (days)	# activates started late	Total start time delay (days)	# activates completed late	Total completion delay (days)	V_1	V_1R	V_2	V_2R	V_3	V_3R	V_4	V_4R
Electrical	11	38	5	21	2	4	0.45	6	0.55	5	0.18	6	0.11	7
Mechanical	13	34	3	9	2	4	0.23	8	0.26	6	0.15	7	0.12	6
Inspection	2	3	0	0	0	0	0.00	9	0.00	9	0.00	8	0.00	8
Hardware distributor	4	7	3	11	2	2	0.75	5	1.57	3	0.50	3	0.29	2
Fibre installation	2	10	0	0	0	0	0.00	9	0.00	9	0.00	8	0.00	8
Controls	5	18	0	0	0	0	0.00	9	0.00	9	0.00	8	0.00	8
Fire protection	2	4	2	8	1	1	1.00	1	2.00	2	0.50	3	0.25	3
Ceiling	4	11	1	1	1	2	0.25	7	0.09	8	0.25	5	0.18	5
Drywall	1	5	1	1	1	1	1.00	1	0.20	7	1.00	1	0.20	4
Painting	1	1	1	9	1	1	1.00	1	9.00	1	1.00	1	1.00	1
City	1	1	1	1	0	0	1.00	1	1.00	4	0.00	8	0.00	8



Note: FCR is Frequency Centrality Rank and SCR is Severity Centrality Rank

Figure 6. Week-by-week consistency between Centrality and Variation Ranks for the 'Painting' Trade.
Note: FCR is Frequency Centrality Rank and SCR is Severity Centrality Rank

evaluated on a monthly basis (see Figures 8 and 9). A monthly rank is the average of four weekly ranks. For instance, rank of Month 1 is the average rank of the first four weeks (Weeks 1, 2, 3 and 4).

The impact of social network on work plan variation can be different from one crew to another. It highly depends on the crew's work type (the type and amount of labour, equipment, space and material). Figures 6–9 show how the consistency between the CRs and VRs is different between the Painting and Electrical crews. The more consistency level was found for Painting indicates that it suffered more (compare to Electrical) from the interferences of the jobsite social networks. In other words, Painting crew was more sensitive to the interferences than Electrical in the studied case. The case-by-case examination will help the project management team and site managers to identify the subcontractor crews suffer more from the jobsite interferences, so they can focus more managerial efforts on these crews to alleviate the impact.

Tables 4 and 5 summarize the correlation analysis between CRs and VRs. The data of all the 43 crews were used in the analysis. The correlation results between weekly CRs and VRs are presented in Table 4, while Table 5 shows the correlation between the monthly

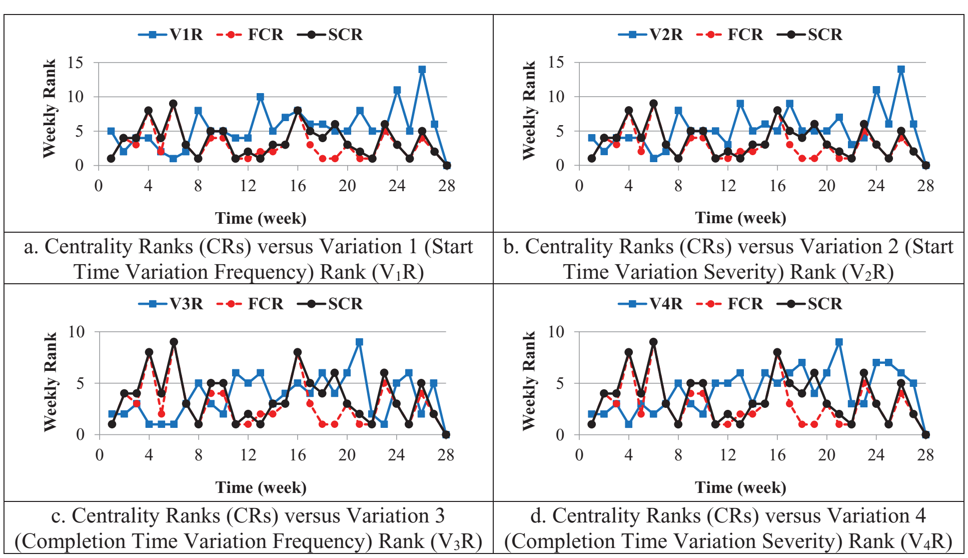


Figure 7. Week-by-week consistency between Centrality and Variation Ranks for the 'Electrical' Trade.

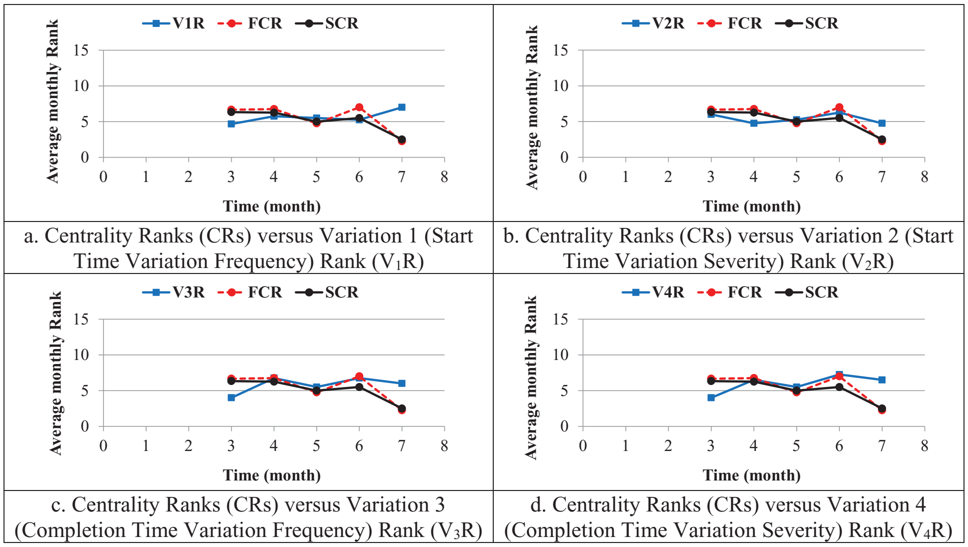


Figure 8. Month-to-month consistency between Centrality and Variation Ranks for the 'Painting' Trade.

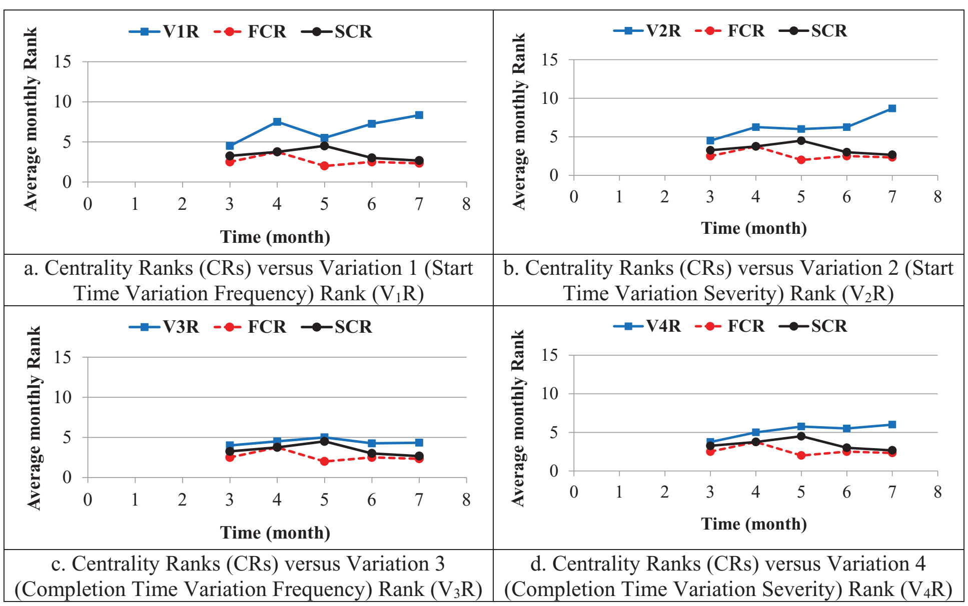


Figure 9. Month-to-month consistency between Centrality and Variation Ranks for the 'Electrical' Trade.

ranks. The most common methods of measuring a monotone association, Spearman and Pearson correlation analysis, were conducted. Spearman correlation is a non-parametric measure of correlation showing how well a monotonic function can describe the relationship between the CRs and VRs. Pearson correlation measures the strength and direction of the linear relationship between them. The results (both weekly and monthly analysis) show that there is a positive monotonic association between CRs and each of the VRs. It indicates that there is a consistency between the impacts of the jobsite social network (from both frequency and severity standpoints) and the variation ratios, i.e. the more centrality, the more variation. By comparing Tables 4 and 5, it can be inferred that the relationship between the CRs and VRs is more noticeable when their association was evaluated on a monthly basis. It should be noted that part of this coefficient improvement is because of sample size reduction when the data of four weeks were combined as a single monthly data point (smoother data). Even though the correlation coefficients do not show a strong correlation between the CRs and VRs, they confirm the positive moderate association between the two. It was not surprising that a strong correlation will not be

Table 4. Correlation analysis results – weekly centrality ranks (CRs) versus weekly variation ranks (VRs).

		Variation ranks (VRs)			
Centrality ranks (CRs)	Correlation method	V_1R	V_2R	V_3R	V_4R
FCR	Spearman	0.16	0.26	0.19	0.21
	Pearson	0.23	0.32	0.20	0.23
SCR	Spearman	0.16	0.26	0.21	0.24
	Pearson	0.22	0.31	0.22	0.26

Note 1: Number of data points was 345.
Note 2: All the correlations are statistically significant at the 0.05 level (P-value <0.05).
Note 3: All the variables are normally distributed.

Table 5. Correlation analysis results – monthly centrality ranks (CRs) versus monthly variation ranks (VRs).

		Variation ranks (VRs)			
Centrality ranks (CRs)	Correlation method	V_1R	V_2R	V_3R	V_4R
FCR	Spearman	0.27	0.35	0.42	0.43
	Pearson	0.31	0.40	0.37	0.38
SCR	Spearman	0.28	0.36	0.43	0.45
	Pearson	0.32	0.40	0.41	0.43

Note 1: Number of data points was 140.
Note 2: All the correlations are statistically significant at the 0.05 level (P-value <0.05).
Note 3: All the variables are normally distributed.

obtained, because there are several uncertainty sources in a construction project other than job site interferences influence the variation ratios. Our focus in this research was on evaluation of the jobsite social network impact, and the moderate positive (linear) correlation obtained for the association appears to be a tangible result.

Discussion

The paper introduced a new approach for analysing the jobsite social network and quantifying its impact on the specialty crews for the first time. It helps the construction managers to understand better the underlying network of the crews in a project. The process of network development and centrality analysis was explained step by step, so it can be repeated in any project based on the existing work plan. Additionally, the research has the following benefits for the project/construction managers and superintendents:

(1) The proposed approach helps the project managers and superintendents to identify the most critical crews with regard to the influences they get from the jobsite social network (those suffer more from the interferences), so they can take proper actions to reduce the conflict potentials. The jobsite social network for each week can be developed based on the existing work plan of that week before the task execution (in our case, one week ahead). Thus, the centrality values of a crew in that week indicate how much influence it is going to receive from the network at that particular period of the project (in our case, next week). Therefore, the influence of jobsite social network on each crew at any time of the project can be predicted based on the centrality values. Then, in order to alleviate the impact, proper actions can be taken by the site managers or crew leaders with regard to those crews under the strong influence. One common way is to adjust the planned schedule. Easy application of approach enables project managers to run the analysis each time they adjust the plan, so they can select the best alternatives (with the lowest impact on the crews). In some cases where schedule adjustment is not feasible (like performing tasks on the critical path of the schedule), project managers can set extra meeting with the leaders of the critical crews to clarify the difficulties they are going to face and find the best solution to reduce the interferences/conflicts.

(2) Although the applicability of the proposed approach was shown for an ongoing construction project in this study, it can be used at the preconstruction stage of the project, i.e. prior to starting the project, where GCs make their work plan/task schedule. GCs can implement this approach to evaluate the developed work plan/task schedule with regard to the jobsite social network influences on the crews. Therefore, they can adjust the task schedule or modify the work breakdown structure to achieve the schedule with the least interference/conflict potentials.

Conclusions

The main aim of this research was to better understand the existing interdependencies among the construction crews in construction phase and the impact of that on their performance. The study first focused on development of the jobsite social network and its immediate area-sharing impact on the construction crews. Then it illustrated the process of developing the jobsite social network over the course of the project and quantify the impact of network on the crews' performance by evaluating the consistency between the characteristic of a crew in the network (centrality indices) and its work plan variation.

The applicability of the approach was shown through a case study, which was construction of a 150,000-square-foot data centre involving a GC overseeing 43 various crews. During the course of this 28-week study, 1200 tasks were performed. Fifty-six networks (28 frequency and 28 severity networks) were developed corresponding to the 28 weeks of the project and centrality analysis was conducted for each week. Results showed that how the topology of jobsite social network, and accordingly, the position and situation of crews change over the course of the project. The proposed approach uncovers the influences sent and received between the crews at any time of the project. The results indicated that there is a positive monotonic association between each of the centrality indices and each of the variability indices: the more influences a crew receives form the network, the more work plan variation (less performance) it will have. The results were predictable since the more interference in the jobsite increases the chance of conflict occurrence. The value of the proposed approach is that it helps the project management team to quantify this impact. However, it should be noted that the impact of jobsite social network on the crews differs from one crew to another. Although the correlation analysis was based on the data of all the crews, for better understanding the approach, the consistency between the network centrality and work plan variation was depicted separately for two selected crews (Painting and Electrical crews). The results showed a sensible consistency for the 'Painting' Crew, while the results for the 'Electrical' crew demonstrated that it suffers less by the influences of the social networks.

Future recommendation

There are three recommendations for future research of jobsite social network:

(1) Since the type and amount of labour, equipment and materials vary from one task to another, in addition to number (frequency) and duration (severity) of the tasks, it is recommended to include the more details about the tasks in development of the networks (for example, the number of workers, the required space for the equipment or being on the critical path) to enhance the accuracy of the jobsite SNA.

(2) The research is limited to a specific project and is based on spatial relationships. The work of construction trades in a project is a function of precedence that cannot be broken. This research did not directly take into account the precedence of a schedule. It considered the working area sharing relationship which is an outcome of working schedule. It is recommended that future jobsite social network includes the schedule precedence in addition to the spatial relationships to have more accurate results.

(3) Common scheduling software (such as Primavera or Microsoft Project) does not include the interdependencies among the crews. They mainly focus on the task dependencies. Jobsite SNA can be added to those software as a new dimension of scheduling. These new features of the software can provide additional information to the managers such as criticality of the tasks' performer.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

Abbasian Hosseini SA. 2015. Social and engineering aspects of construction site management using simulation and social network analysis [Ph.D. dissertation]. Raleigh: North Carolina State University. ISBN 9781339737782.

Abbasian-Hosseini SA, Hsiang S, Leming M, Liu M. 2014. From social network to data envelopment analysis: identifying benchmarks at the site management level. J Constr Eng Manag. 140(8):04014028.

Abbasian-Hosseini SA, Liu M, Hsiang SM. 2017. Social network conformity and construction work plan reliability. Autom Constr. 78:1–12.

Albert A, Hallowell MR. 2014. Modeling the role of social networks in situational awareness and hazard communication. In: Cai H, editor. Proceedings of the 2012 Construction Research Congress Annual Conference. West Lafayette, IN: American Society of Civil Engineers (ASCE). p. 1752–1761.

Allison L, Kaminsky J. 2017. Safety communication networks: females in small work crews. J Constr Eng Manag. 143(8):04017050.

Ballard G, Koskela L, Howell G, Tommelein I. 2005. Discussion of "improving labor flow reliability for better productivity as lean construction principle" by H. Randolph Thomas, Michael J. Horman, R. Edward Minchin Jr., and Dong Chen. J Constr Eng Manag. 131(5):615–616.

Chinowsky P, Diekmann J, Galotti V. 2008. Social network model of construction. J Constr Eng Manag. 134(10):804–812.

Chinowsky P, Diekmann J, O'Brien J. 2010. Project organizations as social networks. J Constr Eng Manag. 136: 452–458. SPECIAL ISSUE: Governance and Leadership Challenges of Global Construction.

Chinowsky P, Taylor J, Di Marco M. 2011. Project network interdependency alignment: new approach to assessing project effectiveness. J Manag Eng. 27(3):170–178.

De Nooy W, Mrvar A, Batagelj V. 2005. Exploratory network analysis with Pajek®. New York (NY): Cambridge University Press.

Dogan S, Arditi D, Gunhan S, Erbasaranoglu B. 2013. Assessing coordination performance based on centrality in an e-mail communication network. J Manag Eng. Doi:10.1061/(ASCE)ME.1943-5479.0000255,04014047.

Hossain L. 2009. Communications and coordination in construction projects. Constr Manag Econ. 27(1):25–39.

Hajifathalian K, Wambeke B, Liu M, Hsiang S. 2012. Effects of production control strategy and duration variance on productivity and work in process: simulation-based investigation. J Constr Eng Manag. 138(9):1035–1043.

Howell G, Laufer A, Ballard G. 1993. Uncertainty and project objectives. Proj Appraisal Jl. 8(1):37–43.

Keung CCW, Shen LY. 2013. Measuring the networking performance for contractors in practicing construction management. J Manag Eng. 29(4):400–406.

Lin S. 2014. An analysis for construction engineering networks. J Constr Eng Manag. 141(5):04014096.

Liu G, Wong L, Chua HN. 2009. Complex discovery from weighted PPI networks. Bioinformatics. 25(15);1891–1897.

Malisiovas A, Song X. 2014. Social network analysis (SNA) for construction projects' team communication structure optimization. In: Castro-Lacouture D, editor. Construction Research Congress 2014: construction in a global network. Atlanta, GA: American Society of Civil Engineers. p. 2032–2042.

Moreno JL. 1960. The sociometry reader. Glencoe: The Free Press.

Opsahl T, Agneessens F, Skvoretz J. 2010. Node centrality in weighted networks: generalizing degree and shortest paths. Soc Netw. 32(3):245–251.

Park H, Han S, Rojas E, Son J, Jung W. 2011. Social network analysis of collaborative ventures for overseas construction projects. J Constr Eng Manag. 137(5):344–355.

Pirzadeh P, Lingard H. 2017. Understanding the dynamics of construction decision making and the impact on work health and safety. J Manag Eng. 33(5):05017003.

Priven V, Sacks R. 2015. Effects of the last planner system on social networks among construction trade crews. J Constr Eng Manag. 141(6):04015006.

Pryke SD. 2004. Analysing construction project coalitions: exploring the application of social network analysis. Constr Manag Econ. 22(8):787–797.

Pryke SD, Zagkli G, Kougia I. 2011. Resource provision ego-networks in small Greek construction firms. Build Res Inf. 39(6):616–636.

Pryke S. 2012. Social network analysis in construction. West Sussex: Wiley.

Seppänen O. 2009. Empirical research on the success of production control in building construction projects [Ph.D. dissertation]. Helsinki: Helsinki University of Technology; p. 175.

Tavistock Institute. 1966. Interdependence and uncertainty: a study of the building industry. London: Tavistock.

Thomas HR, Riley DR, Sinha SK. 2006. Fundamental principles for avoiding congested work areas – a case study. Pract Period Struct Design Constr. 11(4):197–205.

Thorpe T, Mead S. 2001. Project-specific web sites: friend or foe? J Constr Eng Manag. 127(5):406–413.

Wambeke B, Hsiang S, Liu M. 2011. Causes of variation in construction project task starting times and duration. J Constr Eng Manag. 137(9):663–677.

Wambeke B, Liu M, Hsiang S. 2012. Using Pajek and centrality analysis to identify a social network of construction trades. J Constr Eng Manag. 138(10):1192–1201.

Wambeke B, Liu M, Hsiang S. 2014. Task variation and the social network of construction trades. J Manag Eng. 30(4):05014008.

Watkins M, Mukherjee A, Onder N, Mattila K. 2009. Using agent-based modeling to study construction labor productivity as an emergent property of individual and crew interactions. J Constr Eng Manag. 135(7):657–667.

West J. 2014. Collaborative patterns and power imbalance in strategic alliance networks. J Constr Eng Manag. 140(6):04014010.