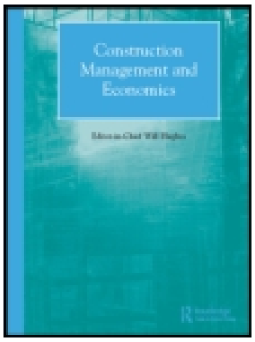

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Measuring and modelling safety communication in small work crews in the US using social network analysis

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Effective safety communication between all parties in a construction project is essential for optimal safety performance. Literature suggests that open safety communication across all levels of the organization enhances safety success. Previous studies have found that open communication and frequent interaction between employees and supervisors differentiate construction companies that have low accident rates from companies that have high rates. Through interviews with construction crew members on active construction projects in the Rocky Mountain region of the US, the patterns of safety communication were identified, modelled, and quantified. Social network analysis (SNA) was utilized to obtain measures of safety communication such as centrality, density, and betweenness within small crews and to generate sociograms that visually depicted communication patterns within effective and ineffective safety networks. A cross-case comparison revealed that the frequency and method of communication are important differentiators between project teams with low and high accident rates. Specifically, top performing crews: (1) have formal safety communication from management on at least a weekly basis; (2) have informal safety communication on a weekly basis; (3) undergo formal safety training; and (4) use all proposed safety communication methods on a monthly basis. In addition, typical SNA metrics, including density, centrality and betweenness, are not significant parameters to distinguish high from low performing crews.

Keywords: Safety, communication, social network analysis, site operations.

Introduction

Although workers in the construction industry account for 8% of the US workforce, statistics show that the industry consistently accounts for 17% of work-related fatalities (US Bureau of Labor Statistics, 2011). Additionally, the National Safety Council (2001, 2002, 2003) reported over 700 fatal work-related injuries and over a million injuries in the construction industry per year. In 2005, 55% of construction work-related deaths occurred in construction establishments that employ 20 or fewer employees (Center for Construction Research and Training, 2008).

As a project-based industry, construction combines multiple organizations and individuals to construct a unique project. In these project-based forms of organizations, interdependence is emphasized over independence (Daft and Lewin, 1993), thus making communication among these teams and individuals critical. Although this is true of construction projects in general, communication is critically important when implementing an effective safety programme. According to Vecchio-Sadus (2007), effective safety communication should include:

- clear communication and open discussion regarding safety issues with all individuals from different levels within one or more organizations;
- encouraging safe behaviour by providing feedback; and
- implementing a lessons-learned programme for safety.

To address the issue of safety communication in small work crews, social network analysis (SNA) was used

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to: (1) quantify the level of safety communication within small and medium-sized construction crews; (2) model the communication patterns and trends within these crews; and (3) analyse the characteristics of high and low safety performance crews with regard to safety communication on construction worksites. SNA is employed for the first time as a potential method to measure and analyse the communication of safety information. SNA is a relatively new research technique to the construction engineering and management (CEM) domain that has recently enjoyed prolific success in CEM research to study project teams (e.g. Chinowsky *et al.*, 2010; DiMarco and Taylor, 2010; Javernick-Will, 2011, etc.). Additionally, the relationships between contract type, project complexity, and litigation concerns have been analysed using SNA (Pryke, 2004). SNA was employed to find the unique characteristics (Wegner, 1987) and understand collaborative working processes (Son and Rojas, 2011) of temporary project teams in large-scale construction projects, focusing on safety communication.

Literature review

This research focuses on the communication of safety information, including the frequency and mode of information exchange. Thus, literature is reviewed regarding safety communication, safety communication modes, and SNA below.

Safety communication

It has been recognized that open communication and frequent interaction between employees and supervisors and among employees are characteristics that distinguish organizations with low incident rates from those with high incident rates (Smith *et al.*, 1978; Zohar, 1980). For example, Smith *et al.* (1978) claimed that immediate verbal feedback to employees with strong safety performance and correction of unsafe behaviours are matters that enhance safety performance. Others showed that the most successful supervisors tend to have open discussions with workers from different trades about safety issues and provide necessary advice (Mattila *et al.*, 1994; Niskanen, 1994; and Simard and Marchand, 1994). Additionally, communication has been listed as one of the top 10 management practices that have a direct positive impact on safety (Hofmann and Morgeson, 1999; Sawacha *et al.*, 1999; Bentley and Haslam, 2001).

Studies have also discussed safety communication within the context of the overall safety programme. For example, Loosemore and Andonakis (2007) found that organizations with in-person safety orientations are more likely to promote behaviour that prevents accidents. They also found that high quantity and quality of safety communication during the project help to overcome language and educational barriers. Similarly, van Dyck *et al.* (2005), Parker *et al.* (2001), and Cigularov *et al.* (2010) all found that strong communication about safety issues was a critical component of total quality and error management.

Consistent and effective safety communication is expected to become even more important in the US in coming years as project teams become more diverse in culture and language. According to the Occupational Safety and Health Administration (US Department of Labor, 2008), communication barriers have begun to increase the proportion of citations that are linked to ineffective safety communication. These expected trends make measuring and monitoring safety communication increasingly important (Emmitt and Gorse, 2003). One emerging method of measuring communication among project participants is social network analysis (SNA). This method may be an effective strategy to rapidly and accurately measure and model safety communication within the various demographics of work crews.

Modes of safety communication

Safety communication was modelled as either formal or informal. Formal safety communication included any sharing of safety knowledge that occurs through channels that are pre-established specifically for safety. Typical examples include formal presentations from upper management, written communication, training and toolbox talks. In contrast, informal communication includes ad hoc communication among individual crew members. For example, informal safety communication could occur when one worker passes by another crew member and informs her of a hazard that has been created by work in transition.

Formal communication from upper management

Upper management support for and commitment to safety is a vital component of a basic injury prevention programme (Jaselskis *et al.*, 1996; Rajendran *et al.*, 2009). Such support and commitment typically requires management to participate actively in safety activities such as toolbox talks and site audits and to provide adequate resources for safety staffing and prevention activities. For example, upper-level managers may visit individual project sites and participate as a team member in pre-task planning events. Management must also send a clear verbal message that safety is a priority, communicate expectations, and reward safe behaviour (Huang and Hinze, 2006). Although previous studies have implied that management must provide safety information to and receive safety information from the network of workers, the volume and frequency of such formal communications have yet to be modelled with empirical and objective data.

Formal written communication

Written safety programmes are an approach for initial evaluation, analysis, and control of workplace safety. These programmes include policies and procedures that are known to maintain a safe working environment. The ultimate benefit of a safety programme is that it serves as a constant reference for workers and managers (New Hampshire Department of Labor, 2010). Other forms of written safety communication may include memos, e-mails, posters, and signs (Hallowell, 2011).

Formal safety training

Safety training refers to scheduled instruction that facilitates the development of safe work practices, technical skills, and knowledge of safety protocol. Safety training can also refer to knowledge and skills that construction workers need to effectively respond to hazards (Hale, 1984). Training can be delivered through classroom instruction, videos, online modules and hands-on simulations (US Department of Labor, 2011). A study by Sawacha *et al.* (1999) confirms the safety training is vital because it increases safety awareness and reaction. Training may be provided to the crew by an internal member of the organization or outsourced to an external consultant (Hallowell, 2011) and is considered by Rajendran *et al.* (2009) to be the foundation of an effective safety culture.

Formal toolbox talks

Toolbox talks are regular safety meetings that are typically performed on site immediately before the work takes place (Huang and Hinze, 2006). The content, frequency, and structure of these meetings vary greatly among organizations. Some researchers suggest that these meetings should take place before each new work task and should be facilitated by formal and documented job safety analyses (Boud *et al.*, 2009). Based on the results of previous research (e.g. Hurst *et al.*, 1996; Jaselskis *et al.*, 1996), these discussions are expected to be an important element that contributes to the successful development of an effective safety network.

Informal communication among workers

Approximately 70% of organizational communication is informal (De Mare, 1989). Informal communication typically takes the form of ad hoc conversations and announcements based on the current exposures on worksites that may be urgent and alarming. Surprisingly, informal safety communication within crews has yet to be studied.

Social network analysis

Social network analysis (SNA) was first developed by Jacob Moreno to study the social interactions of groups. Moreno (1960, p. 17) defined SNA as 'A quantitative analytic tool used to study the exchange of resources among different groups'. Alternatively, it is defined by Haythornthwaite (1996, p. 323) as 'An approach and set of techniques used to study the exchange of resources among actors'. Regardless of definition, the main benefit of SNA is that it is an analytical tool that allows a researcher to identify patterns of social relations among many actors with visual models and objective metrics that are grounded in scientific theory (Wasserman and Faust, 1994). SNA also facilitates the analysis of the structure of communication patterns that typically are latent in other observational research techniques. In the past decade, SNA has been used as research method within the social and behavioural sciences to model the relationships among different actors within one or more organizations (Hawe and Ghali, 2008).

At a minimum, social network data consist of actors and relationships (or links) among actors. Additional data can be collected on attributes, or characteristics of each actor, as well as additional insight into their relationships, for example, the frequency of communication or mode of knowledge exchange. In order to analyse a social network it's essential to plot a diagram that depicts the proximal relationships among actors (Wasserman and Faust, 1994). These 'sociograms' model nodes as actors (e.g. crew members) and the links between actors as the relationship of interest (e.g. communication about injury prevention). Accurate and meaningful network visualization depends on the underlying mathematical analysis and methods implemented to gather input data. Once valid and reliable input data are obtained and appropriate and accurate mathematical models are designed, SNA can produce several metrics that may serve as leading indicators of network performance.

SNA is an accepted analytical technique that has seen widespread use. For example, SNA was used in supply chain management (Silva *et al.*, 2008), terrorist networks (Ressler, 2006), and tracking the spread of AIDS (Morris, 1993). In construction, SNA models have been used to identify strengths and weaknesses within and among projects teams (e.g. Taylor and Bernstein, 2009; Comu *et al.*, 2011) and organizations to improve project performance (e.g. Chinowsky *et al.*, 2008). SNA metrics will be reviewed briefly below. For a detailed overview of SNA metrics, the reader is encouraged to review Freeman (1977).

Network density

Density is a measurement that indicates the ratio of the actual links or relationships available between the network actors to the maximum possible number of links that the network could have (Borgatti and Everett, 2006). The higher the density value, the more likely it is that actors are connected to each other (see Equation 1). Connections are defined by information or knowledge exchange that occurs through formal correspondence or ad hoc communication that is established to solve problems.

$$\Delta = \frac{L}{g(g-1)} \tag{1}$$

where Δ is the network density, L is the number of existing connections (relationships) in the network, and g is the total number of actors.

Actor centrality

Centrality can be measured for each individual actor or for the network as a whole. Given the context of safety communication, where it is important that each crew member has communication channels to receive or provide information pertaining to safety, our research focused on the centrality of individual actors. The level of centrality of an actor measures the total number of direct relationships that any actor in the network has with other actors in the network (Freeman, 1977). Equation 2 is used to compute the standardized degree of centrality for a particular individual.

$$C_D\ (\text{actor x}) = \frac{(\text{cD (actor x)})}{(g-1)} \tag{2}$$

where C_D (actor x) is the total number of relationships that the actor x has (in or out), and $(g - 1)$ is the maximum possible number of relationships that actor x can have, where g is the total number of network actors.

Betweenness

Betweenness measures the total number of occurrences when a specific actor is required to connect two disparate actors in a network (Freeman, 1977). An actor with a high degree of betweenness is sometimes referred to as a 'gatekeeper' of information. These individuals may impede information flow or greatly disrupt the network if they are removed.

These metrics represent the heart of the hypothetical constructs when modelling communication patterns. We use SNA as a tool to study the safety communication patterns among actors in small building construction crews with the goal of determining if the SNA metrics and patterns observed may be used as leading indicators of safety performance.

Research methods

To determine safety communication patterns among crew members, the research team administered questionnaires to nine crews on active building construction projects in the Denver Metropolitan area of the US. Before surveys were administered, the team discussed the objectives of the study and the research protocol with the safety manager or project superintendent. Once this introduction was complete, the survey was administered to a small crew on the project. To avoid bias, the research team insisted on administering the surveys directly to the worker rather than allowing the surveys to be distributed and described by the project leadership. Additionally, to ensure that the crew members understood the survey, both Spanish and English versions of the questionnaire were designed and the survey orientation was provided in both English and Spanish by bilingual researchers. This direct communication from the research team to the workers also allowed the research team to provide detailed directions and answer questions. In addition, because the research aimed to determine safety communication patterns of a crew, it was of utmost importance that *everyone* on the crew participated in the study. As a result, surveys were administered and analysed for a complete network, or a stable crew. If even one individual in the crew declined to participate or was not present, the results were not analysed.

For the purpose of our study, a crew included all field-level employees and field-level managers who (1) work for the same employer in the same physical location; (2) have worked together for at least half of the project duration; (3) are dedicated to the same project; and (4) participate in a collaborative work environment. Thus, upper-level managers who may visit the site occasionally or short-service employees are not included. The limitations associated with these boundary conditions are discussed in the conclusions.

Several constraints were placed on the selection of case crews to ensure internal and external validity of the results. Only stable crews that had been working together as one unit on a project that was at least 50% complete were included. This constraint prevented the analysis of ad hoc or transient crews that the team did not intend to study. Additionally, the crew size was limited to 5 to 12 members, including field-level managers. This constraint was imposed to prevent variations that exist when networks of dissimilar sizes are analysed and compared. By constraining the size of the networks, a cross-case comparison of network patterns and calculations was more meaningful. Table 1 shows the salient demographics of the participating crews. Because this effort was largely exploratory (i.e. the first known application of SNA to the safety domain), the research team conducted the interviews in an iterative process as new information was received and challenges were recognized. Fortunately, the project participants agreed to provide data during follow-up interviews. This iterative process was important for preserving internal validity; for example, the research team returned to determine the frequency of use of each mode identified to communicate safety knowledge.

The English version of the questionnaire administered to crew members is shown in Figure 1. The respondents were asked to provide demographic information such as their name and position. These attributes were linked to nodes (or individuals) in the network. Each individual's name was redacted and replaced with pseudonyms to protect the workers' identities. In the second component of the survey respondents were asked to record to whom they *provided* safety information and the average frequency of communication using each of the five communication modes, namely formal communication with management, written communication, training, informal discussions and toolbox talks. The third component of the survey was identical to the second except the respondents were asked to indicate from whom they *received* safety information and the average frequency of this communication for each of the five communication modes.

Although the questionnaire was administered to a complete network, we used an egocentric data collection approach where each individual was asked to identify with whom they communicated safety information versus responding to a survey pre-populated with crew members' names. Because the crew size was small and every member of each crew participated, the resulting data included all members. This is important because having data from a complete crew enhances the internal validity of the analyses.

The data were coded and sorted using MS Excel so that they were compatible with the most standard SNA modelling software: UCINET. This software system computes the aforementioned SNA metrics, which are nearly impossible to calculate by hand or through MS Excel functions once project networks exceed four members. When coding the frequency of safety communication, the following scheme was used: 1 = once a month; 2 = bi-weekly; 3 = weekly; 4 = once a day; and 5 = more than once a day.

Once all data were coded and entered into UCINET, the software system produced the aforementioned metrics and sociograms. We plotted the sociograms using NetDraw within UCINET for each crew based upon metrics collected. These data can be filtered to report, visualize and analyse singular or combined metrics. For example, direction, frequency and mode of exchange can be analysed individually or in combination (e.g. the receipt of safety information on a weekly basis or written safety communication that occurs on a weekly basis).

Table 1 Relative safety performance summary (high to low)

Crew	Trade	Crew size	RIR	Percentile rating	Safety performance	Percent of maximum performance
5	Drywall	10	2.8	85%	0.304	1.000
9	Carpentry	5	3.9	90%	0.231	0.760
6	General	12	4.1	90%	0.220	0.723
7	Drywall	5	4.4	95%	0.216	0.711
2	Glazing	7	5.4	90%	0.167	0.549
3	HVAC	5	6.8	95%	0.140	0.460
4	HVAC	7	6.8	95%	0.140	0.460
8	Carpentry	6	5.4	75%	0.139	0.458
1	Electrical	5	12.1	100%	0.083	0.272

Your Name: ________________________________

Your Position: ________________ **Company:** ________________

To whom on your crew do you **PROVIDE** safety information to, how often do you communicate, and through which means?												
Name of individuals who you **PROVIDE** safety information to		Frequency of communication (check boxes)					Most common mode(s) of communication (check all boxes that apply)					
First Name	Last Name	once a month	bi-weekly	weekly	once a day	more than once a day	Formal communication (mgt role)	Written communication	Training	Informal discussions	Toolbox talk	Other (please specify)
Participant 1				×				×	×			
Participant 2				×		×	×	×				
Participant 3				×							×	
Participant 4				×	×					×	×	

Figure 1 English version of the SNA questionnaire

Composite measure of safety performance

One of the goals was to correlate SNA metrics and sociogram characteristics with lagging indicators of safety performance. Typically, safety performance is measured using a company's OSHA recordable injury rate (RIR) or experience modification rate (EMR) (Jaselskis *et al.*, 1996). According to the US Department of Labor (2004), RIR is the number of recordable injuries and illnesses that have occurred over a certain period of time (usually one year). This metric is usually used to compare any construction company's safety performance against the national or state averages. Unfortunately, an RIR is rarely recorded for a specific work crew. Additionally, the actual safety performance may be related not only to the organization's RIR but also to the relative performance of the specific crew within the company as a whole. Consequently, a composite safety metric was used to compare the safety performance of the case crews. Although different trades were included in the case studies, and the variability in work performed may inherently lead to differences in RIR, the Center for Construction Research and Training (2008) has reported very consistent injury rates for the selected trades over the past decade.

Following the survey administration the research team requested that an upper-level manager who is in a position to directly oversee a large proportion of the organization's work crews (e.g. safety manager or programme manager) provide the organization's RIR for the past calendar year and a rating of the target crew's relative safety performance within the organization (i.e. percentile rating). The composite safety score was then calculated by multiplying the inverse of the RIR by the percentile rating. The data were then normalized by computing a relative performance metric by dividing each composite safety metric by the maximum metric achieved ('percent of maximum' rating). The score of 1.0 corresponds to the highest performing crew in the study and all other metrics are measured against the performance of this crew. These computations can be achieved using Equations 3 and 4.

$$\textit{Crew safety performance} = \frac{\textit{safety performance percentile}}{\textit{recordable injury rate } (RIR)} \quad (3)$$

$$\textit{Percent of maximum} = \frac{\textit{crew safety performance}}{\textit{the highest safety performance among the } 9 \textit{ crews.}} \quad (4)$$

Once the necessary safety performance data had been collected and analysed, the crews were sorted by relative performance to identify the relative tiers of performance as shown in Table 1. Three clear tiers emerged based on their percentage of maximum safety performance: the top three performers and the three bottom performers are the two selected groups in analysing the data; the third (or the middle) performers were analysed but not compared.

Data analysis and discussion

The results revealed interesting trends. On a macro level, toolbox talks were found to be the most commonly used and most frequently used communication mode. In fact, all nine crews used this communication mode on at least a weekly basis. Alternatively, only three of the nine crews had any form of written safety communication. After a detailed analysis of the data was conducted, several important trends were observed. These findings are described below along with their supporting data. One may note that, because this is an exploratory study, the findings below can be used as propositions for future studies.

Finding 1: Top performing crews receive formal safety communication from management on at least a weekly basis

Based on the network density values, the three crews with the highest relative safety performance have formal safety communication from management at least weekly while the bottom three performers have very little to no formal management safety communication between workers and managers. Table 2 highlights these data.

Figure 2 shows the sociogram for the crew with the top relative safety performance (crew 5) and Figure 2 (B) provides the sociogram for the crew with the lowest safety performance (crew 1). These sociograms depict the number and patterns of connections that exist for management providing safety information to workers in the network at least weekly. As one can see, the top performing network contained many connections with the actor J, the upper-level manager and the lowest performing network included only one communication link between management, actor B, and the workforce on a weekly basis.

These data show that the interactions between workers and managers may be important influencing factors for safety performance. This finding supports previous research findings that open and frequent communication between supervisor and employees differentiates the high from the low safety performance crews (Smith *et al.*, 1978; Zohar, 1980; Cigularov *et al.*, 2010).

Table 2 Formal communication network density (weekly)

	Crew	Network density
Top crews	5	11%
	6	14%
	9	10%
Bottom crews	8	5%
	3	0
	1	5%

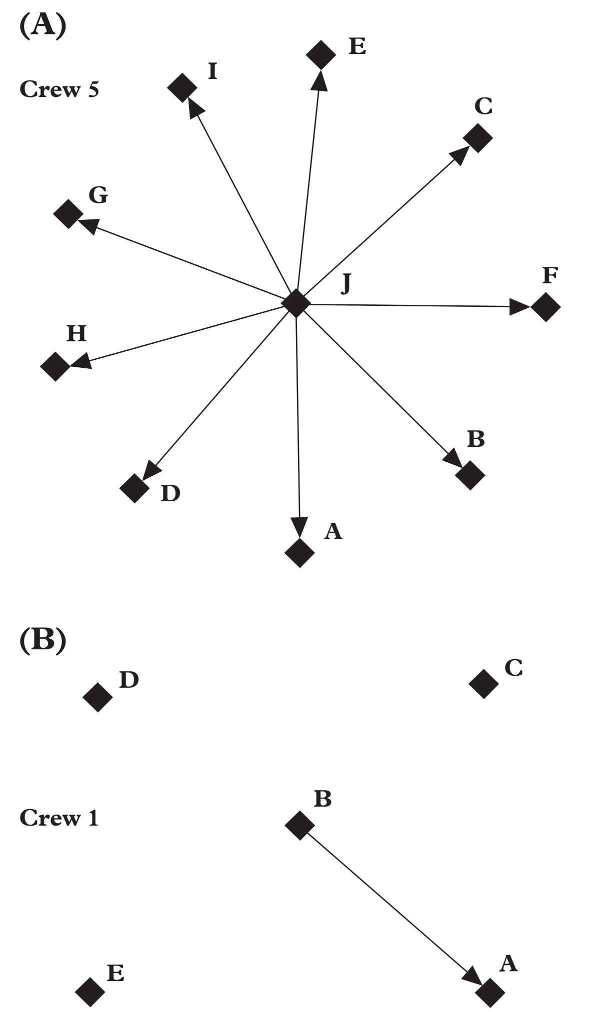


Figure 2 Selected weekly formal safety communication sociograms
Notes: The letters (A, B…, etc.) refer to the actor name in the network. Each actor was represented by a ‘node’ ◆. Lines with arrows refer to the communication link ‘relationship’.

Table 3 Informal weekly safety communication network density

	Crew	Network density
Top crews	5	80%
	6	23%
	9	30%
Bottom crews	8	0
	3	0
	1	15%

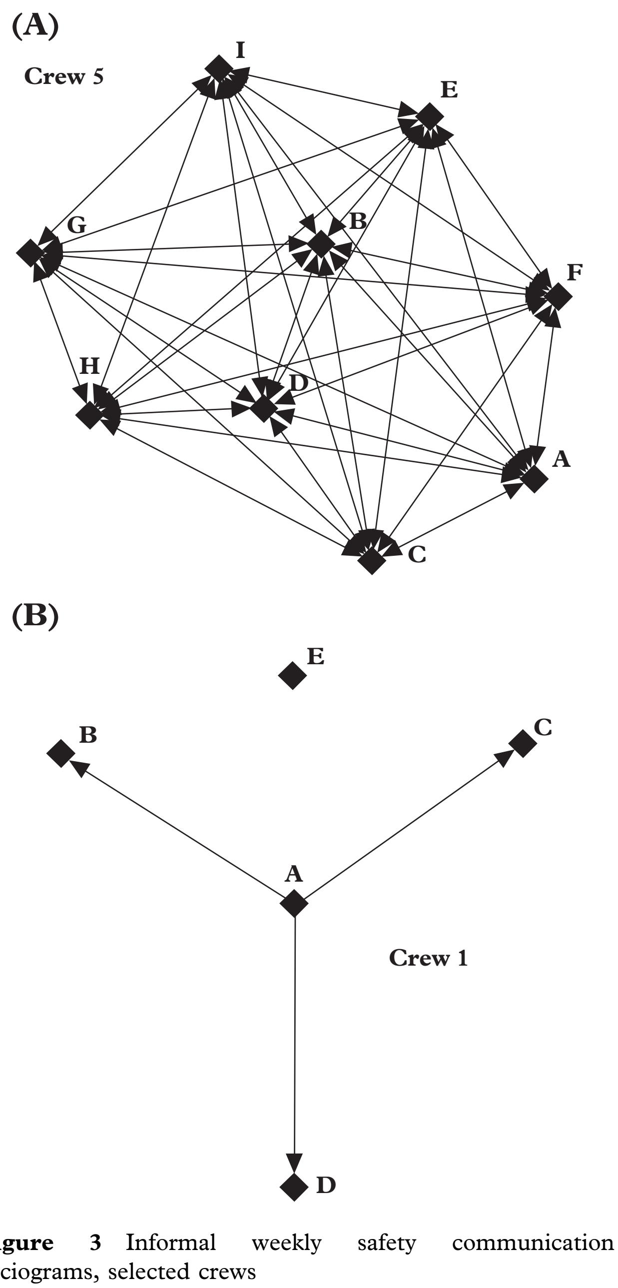


Figure 3 Informal weekly safety communication sociograms, selected crews
Notes: The letters (A, B…, etc.) refer to the actor name in the network. Each actor was represented by a 'node' ◆. Lines with arrows refer to the communication link 'relationship'.

Finding 2: Top performing crews have informal weekly safety communication on at least a weekly basis

Workers within high performing crews tend to share safety information in an ad hoc manner on a weekly basis. As shown in Table 3 and Figure 3, the greater the number of crew members that are connected through informal safety communication on a weekly basis, the better the relative safety performance.

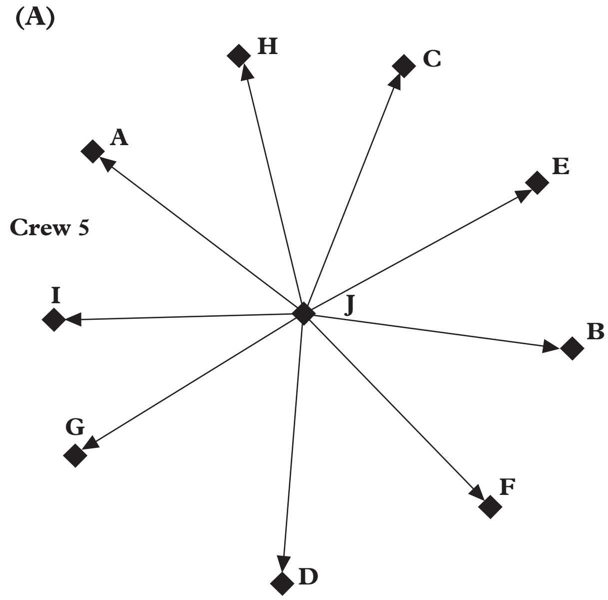
In crew 1, the foreman, actor A, is the only individual who shares safety information informally on a weekly basis; conversely, the links in crew 5 are numerous and seemingly independent from the crew members' positions. This finding is also theoretically supported from previous research that found that cohesive networks tend to have shared attitudes and behaviours, which enhance performance (Seashore, 1977; Wyer, 1966). Additionally, through strong and frequent informal connections crews have increased capacity to manage potential errors before they lead to an incident (van Dyck *et al.*, 2005).

Finding 3: High performing crews provide and receive formal safety training on at least a monthly basis

The results indicate that training is an essential communication mode for high performing crews and tends to occur on at least a monthly basis. In high performing safety networks, supervisors were responsible for providing monthly or weekly safety training for their workers. Figure 4 depicts the two top performing crews. These crews have management-led safety training that enhances the density of the safety communication network drastically. In comparison, low performing crews had no connections among members when the data were dichotomized for monthly communication. As a result, the sociograms for low performing crews are not shown (see Table 4 for crew metrics). As indicated in past research, regular training is an essential component of strong safety performance and safety awareness (Shimmin *et al.*, 1980; Sawacha *et al.*, 1999; Rajendran *et al.*, 2009).

Finding 4: High performing crews use the all proposed safety communication modes studied

Interestingly, one of the factors that distinguished high performing from low performing crews was the



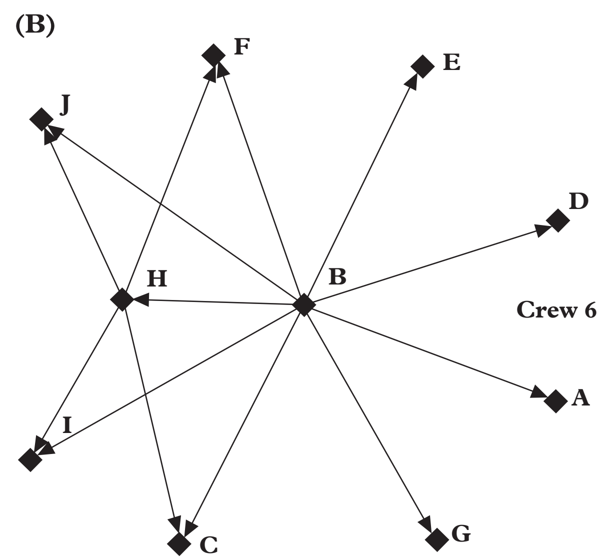


Figure 4 Safety training communication sociograms in high performing crews on a monthly basis
Notes: The letters (A, B…, etc.) refer to the actor name in the network. Each actor was represented by a 'node' ◆. Lines with arrows refer to the communication link 'relationship'.

variety of communication modes used, regardless of their frequency. As shown in Table 5, the three top performing firms used all communication modes while the low performing crews used only a portion of the modes. This finding is supported by March and Simon (1958) who showed that the general communication structure of a successful organization must include both formal and informal modes.

Table 4 Network density degrees for safety training on a monthly basis for high and low performing crews

	Crew	Network density
Top crews	5	20%
	6	16%
	9	20%
Bottom crews	8	0%
	3	0%
	1	0%

Finding 5: The general SNA metrics other than density were not significant measures that distinguish the high from the low performing crews

Although one of the research teams' initial hypotheses was that the typical SNA metrics (e.g. betweenness) would correlate with the relative safety performance metrics on a macro basis when all communication modes were considered, these correlations were not supported by the data as shown in Table 6. Instead, the findings showed that only density was significant in the analyses. Effective networks were found to have a high degree of density for the training and management communication modes but diffuse networks were shown to be more effective for informal communication. These results extend existing findings that effective communication of knowledge is contingent on many factors, including type of knowledge exchanged and the mode or method of knowledge exchange (Javernick-Will and Levitt, 2010). Specifically, it adds to existing literature that has shown that the frequency of exchange, in combination with the mode, is vital for effective communication. The common finding for safety networks, however, is that a variety of communication modes must be used where a large proportion of crew members participate in the safety information exchange to achieve excellent safety performance.

Limitations

Although the data support several new conclusions, the study is limited in its external and internal validity in several ways. First, the scope of inference is statistically limited to the State of Colorado in the US because all participating crews worked and resided in this region. Second, all crews were actively working on building construction projects. Therefore, the results only extend theoretically to infrastructure and other construction projects. Third, although nine crews is a sufficient sample size for case study

Table 5 Safety communication modes used by high and low performing crew

	Crew	Formal communication	Written communication	Training	Informal discussion	Toolbox talk
Top crews	5	X	X	X	X	X
	6	X	X	X	X	X
	9	X	X	X	X	X
Bottom crews	8	0	0	0	X	X
	3	0	X	X	0	X
	1	X	0	X	X	X

Table 6 SNA metrics for high and low performing crews

		Provide information	Receive information
	Crew	Network density	Network density
Top crews	5	90%	90%
	6	20%	35%
	9	19%	22%
Bottom crews	8	17%	7%
	3	5%	20%
	1	40%	60%

research and network analyses, the results were only analysed qualitatively. Statistical analyses would require a much larger sample. Fourth, the risks that each participating crew could be exposed to were not considered. A future research study is recommended to explore how variable risks affect safety communication behaviours. Fifth, the size of the crews was limited to 5 to 12 members. Thus, the results only theoretically extend to small crews within this size range. Sixth, all work crews were stable and short-service employees were not included so the results do not apply to transient work crews. Finally, only hierarchical position was collected as demographic information for each crew member. Despite these limitations, the findings of this study confirm past research and provide compelling qualitative evidence that the patterns of safety communications for various modes are predictive indicators of safety performance.

Conclusions and recommendations

Past research has revealed that safety communication in various modes is important to achieve safety success in large construction companies. However, the frequency and structure of effective safety communication within each mode and within small project teams have yet to be investigated. To address this gap in knowledge, SNA was used to model and measure safety communication within small crews in nine construction firms in the Denver Metropolitan region of the US. The results indicate that the characteristics of requisite safety communication for small firms are consistent with previous studies of large firms but that the actual patterns of effective information exchange are dependent on the communication mode. Thus, safety communication appears to be a much more complex issue than discussed previously.

We recommend future research that explores this topic in greater detail and confirms the findings presented with a large dataset and statistical tests. Additionally, given the changing demographics of the US workforce, future work could attend to the importance of personal attributes on network communication structure and formation. Specifically, the language barriers are likely to affect frequency and mode of safety communication for effective performance. Qualitative comparative analysis (QCA) could be employed to determine the combinatorial pathways, along with necessary and sufficient causal conditions, that lead to certain levels of safety performance. Additionally, QCA could be used to establish whether multiple combinations of frequency and mode lead to differing outcomes (for instance, monthly exchange of safety communication using formal mode *and* weekly exchange of safety communication using informal modes). Finally, research into inter-organizational safety communication, particularly among crews representing different employers, is suggested to model the dynamic nature of construction projects.

It is expected that advanced knowledge of safety communication networks could have the potential to transform the structure of safety programmes. Additionally, the use of SNA metrics may serve as a very efficient leading indicator of safety performance that can be quickly measured and modelled as a project commences. Such data could be used to evaluate actual network patterns and be compared with ideal networks to identify connections that should be bolstered. Based on the observations in this study, SNA could be a very fruitful research technique in the safety domain because so many safety management issues are related to social interactions and teamwork.

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