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Abstract

Theories developed to explain work health and safety performance (WHS) in the construction industry posit that better outcomes are achieved when WHS is considered in early project decision-making. Consistent with this, legislation has been enacted requiring that the WHS of construction workers be considered in pre-construction (i.e, project planning and design) decision-making. The research aimed to examine the extent to which the position of the constructor in communication networks, including those before the commencement of construction, was related to the quality of WHS outcomes realised. Twenty three cases were drawn from ten participating construction projects in Australia and New Zealand. Social network analysis was used to mathematically and graphically model information exchanges in 13 of these cases. For each case, the quality of WHS risk control outcomes was measured. This measurement was based on an established "hierarchy of control" in which risk controls are classified in descending order of effectiveness from the elimination of a hazard (the most effective) to the reliance on personal protective equipment (the least effective). Social network metrics were calculated reflecting: (i) the ratio of actual links among parties in the project network relative to the maximum number of links possible (network density); and (ii) the extent to which the constructor communicated with other parties in pre-project planning and design stages (the constructors' degree centrality). Network metrics were compared for cases in which the risk control scores were higher and lower than average. The results showed a significant difference in constructors' pre-construction degree centrality for cases with high and low risk control scores. The results provide preliminary evidence as to the potential WHS benefits of ensuring that constructors' knowledge about construction methods, materials, WHS risks and means of risk control, are integrated into pre-construction decision-making. The research also highlights the potential usefulness of social network metrics in WHS performance measurement and benchmarking.

Keywords

Risk control, health and safety, construction planning and design, constructor involvement

Introduction

Work health and safety in the construction industry

The construction industry performs poorly in work health and safety (WHS) relative to other industries. In Australia between 2008–09 and 2010–11, 123 construction workers died from work-related injuries. The construction industry fatality rate is 4.26 fatalities per 100,000 workers, nearly twice the national rate of 2.23 (Safe Work Australia, 2012a). Further, in the same period, construction accounted for a disproportionate number of serious workers' compensation claims. Despite employing 9% of the Australian workforce, construction accounted for 11% of serious workers' compensation claims. On average, 39 claims were made each day by construction industry employees who required one or more weeks off work because of work-related injury or disease. As with fatalities, the rate of serious claims is considerably higher among construction industry employees than the national average (19.9 compared to 13.0 per 1000 workers).

Theoretical models developed to explain the occurrence of accidents, injuries and fatalities in the construction industry reflect the fact that accidents can often be traced back to decisions made before construction work commenced (i.e, during project planning and design stages). For example, Suraji et al. (2001) describe the complex interaction of factors that contribute to the occurrence of construction site accidents. They propose a Constraint-Response accident causation model. The model holds that the parties involved in each stage of the construction project lifecycle (conception, design, and construction) experience constraints on their decision making. Their responses to these constraints, in turn, constrain the actions of participants in the subsequent stages. Ultimately, unless carefully managed, the cumulative effect of constraints and responses will be experienced as hazardous site conditions, inappropriate work practices, or unsafe actions at the construction site. Thus, accident causes can be traced back from the immediate site level conditions, actions and practices, to the planning and control activities of site supervisors and managers, to subcontractors' constraints and responses, to principal contractors' constraints and responses, and to the constraints and responses experienced by designers and clients in the design and project conception stages (Suraji et al., 2001).

Similarly, a research team based at Loughborough University developed holistic model of accident causation by carefully investigating the causes of 100 construction accidents. The research team obtained information from people involved in accidents, including the victims and their supervisors, to describe the processes of accident causation in construction. Based on their analysis, they developed a construction accident causality (ConAC) model. The ConAC model identifies originating influences affecting accidents in construction as including:

- client requirements
- features of the economic climate
- prevailing level of construction education
- design of the permanent works
- project management issues
- construction processes, and
- the prevailing safety culture and risk management approach.

Haslam et al. (2005) comment that in almost 50% of the cases included in the analysis, a change to the permanent works design could have reduced the level of risk that preceded an accident.

Early research investigating safety in design in the construction industry sought to establish an empirical link between design activity and WHS outcomes, specifically the occurrence of accidents, injuries or fatalities. This research largely involved retrospectively analysing the causes of accidents to assess whether design was a cause. Retrospective analyses contribute to building the case for safety in design. However, they have limitations. It may not be warranted to conclude that there are direct links between design decisions and a workplace accident. A researcher may attribute a direct link even though the relationship is tenuous – an outcome that Lundberg et al. (2009) termed 'what-you-look-for-is-what-you-find'. Retrospective analysis alone cannot illuminate the relationship between implementing safety in design and achieving improved WHS outcomes.

The objective strength of the link between design and WHS performance is still unclear, and remains a subject of debate. Researchers have been justifiably cautious about quantifying the potential for safety in design to produce improved WHS outcomes in construction. For example, Gibb et al. (2004) choose their words carefully when stating that design modifications had the potential to reduce the risk of almost half of the construction accidents they analysed, but might not necessarily have prevented those accidents from occurring. Further, in focusing on outcomes (that is, accidents), retrospective analyses tell us little about current safety in design initiatives and tools, or their potential impact on future WHS performance in the construction industry.

Research in 'live' projects is helpful for better understanding the relationship between WHS management activities that take place during a construction project's pre-construction stage and actual WHS performance.

Aim

The research explored the relationship between the flow of communication among project participants in a construction project and the quality of WHS risk controls realised during the ensuing construction stage of the project. This included communication flow prior to the commencement of construction, i.e., in the planning and design stages of a project's life cycle. In particular,

- the quality of controls used to mitigate construction WHS hazards/risks was measured,
- the involvement of the construction contractor in project communication networks was quantified; and

- the relationship between the construction contractor’s prominence in the project communication network and the quality of WHS risk control outcomes was assessed.

In the remaining sections of this paper a short overview of the Australian policy context relating to safety in design is provided to provide the context for the research. This is followed by a brief explanation of some of the structural challenges associated with the implementation of safety in design in the construction industry. The importance of integrating construction process knowledge into early project planning and design decisions is discussed. The choice of methodological approach used to explore project communication networks is briefly explained. The comparative case study research design and methods used to collect and analyse research data are described in detail. The results of the analysis are presented, using two detailed narrative case descriptions. Finally, the research results are discussed with particular reference to the implications for construction project communication networks and the implementation of safety in design.

The Australian policy context for safety in design

The construction industry has been identified as an industry requiring priority action in the *Australian Work Health and Safety Strategy 2012-2022*. This Strategy establishes ambitious targets over a ten year period. These targets include: (i) a reduction of at least 20 per cent in the number of worker fatalities due to injury; (ii) a reduction of at least 30 per cent in the incidence rate of claims resulting in one or more weeks off work; and (iii) a reduction of at least 30 per cent in the incidence rate of claims for musculoskeletal disorders resulting in one or more weeks off work.

Promoting safety in design is a key action area in the *Australian Work Health and Safety Strategy 2012-2022*. Strategic outcomes to achieve by 2022 are:

- structures, plant and substances are designed to eliminate or minimise hazards and risks before they are introduced into the workplace, and
- work, work processes and systems of work are designed and managed to eliminate or minimise hazards and risks (Safe Work Australia 2012).

It is argued that designers are better positioned to make decisions that eliminate hazards before work commences at a construction site. Adopting this perspective has led to WHS legislation in all Australian states and territories which now specifies WHS duties for designers of buildings and structures. This means that responsibility for some aspects of WHS have been pushed up the supply chain and now rest with professional contributors in the planning and design stages. Behm (2005, p.608) notes:

> While the constructor will always bear the responsibility for construction site safety, utilization of the [safety in design] concept allows design professionals to participate in enhancing site safety.

Structural challenges to integration of WHS

Notwithstanding the growing emphasis integrating WHS consideration into project decision-making in the planning and design stages of projects, the extent to which WHS has actually been improved by these policy initiatives remains unclear. One challenge lies in the degree to which there is vertical segregation between participants engaged in the initiation, design, production, use and maintenance of facilities (Atkinson and Westall, 2010). In particular, the traditional separation between the design and construction function can impede the development of shared project goals (Baiden and Price, 2011) and can negatively impact project outcomes (Love and Gunasekaran, 1998). A recent review of WHS in the UK construction industry identifies separation and poor communication between the design and construction functions as a causal factor in construction fatalities (Donaghy, 2009).

The organizational and contractual separation of the design and construction functions reduces the possibility of free flowing communication between constructors and designers (see, Atkinson and Westall, 2010). This is a problem because communication is critical to the effective performance of construction project teams.

There is emerging research evidence that design professionals are not sufficiently well versed in knowledge of construction methods and/or WHS to fulfill their responsibilities for safety in design (Yates and Battersby 2003). Even in the UK, where the Construction Design and Management Regulations have been in place for some 18 years, Brace et al. (2009) report that "many designers still think that safety is 'nothing to do with me,' although there are a small cohort who want to engage and are having difficulty doing this because they do not fully understand what good practice looks like" (p. 12). Consequently, Donaghy (2009) recommended that accrediting bodies establish specific requirements to embed WHS in the education of all professionals engaged in the delivery of construction projects, particularly those with "upstream" roles.

It is frequently stated that collaborative or integrated forms of project delivery improve buildability and, by implication, have the potential to also improve WHS (Bresnan and Marshall, 2000; Kent and Becerik-Gerber 2010). However, Ankrah et al. (2009) comment that the procurement method cannot, of itself, create a positive cultural orientation towards WHS. Similarly, Atkinson and Westall (2010) point out that that the adoption of an integrated project delivery approach does not guarantee positive safety outcomes.

Integrated project delivery mechanisms create favourable conditions for the integration of WHS into construction project planning and design activities, but actual WHS improvements are likely to occur as a direct result of the increased communication and information exchange among project participants. Little research has investigated the link between communication networks in construction projects and WHS performance. The present research sought to address this knowledge gap.

Social network analysis

The research utilised social network analysis to explore and understand communication in construction project networks. Social network analysis is an analytical tool to study the exchange of resources among actors in a network. Wasserman and Faust (1997, p. 17) define network actors "discrete individual, corporate or collective social units." Using social network analysis, patterns of social relations among actors can be represented in the form of visual models (known as sociograms) and described in terms of quantifiable indicators of network attributes. In a sociogram, actors are represented as nodes. To varying extents, these nodes are connected by links which represent the relationships between actors in the network. Social network analysis is particularly useful in the analysis of relationships, information exchanges and communication patterns among organizations. This is important because previous research has highlighted the way in which inter-organizational relations and social context influence organizational behaviour in the construction industry (see, for example, Harty 2008; Schweber and Harty 2010).

Social network analysis has been recommended as a useful method for understanding and quantifying the roles and relationships of actors in construction project coalitions (Pryke, 2004; Chinowsky et al. 2008). The technique has been used to analyse knowledge flows among construction project participants (see, for example, Ruan et al. 2012; Zhang et al. 2013). Network characteristics have also been used to explain failures in team-based design tasks (Chinowsky et al. 2008) and identify barriers to collaboration that arise as a result of functional or geographic segregation in construction organizations (Chinowsky et al. 2010). More recently, Alsamadani et al. (2013) used social network analysis to investigate the relationship between safety communication patterns and WHS performance in construction work crews.

Methods

Case study design

The research adopted a comparative case study design. A case study approach was favoured for the rich data that it produces (Orum et al., 1991; Eisenhardt, 1989; Fellows and Liu, 1997; Yin, 1994). Data were collected from ten construction projects in Australia/New Zealand. In each project "features of work" (i.e, specific building elements) were purposefully identified by project participants in consultation with the research team (see also Table 1). These features of work constituted discreet cases in the analysis. A feature of work was selected if: (i) all participants involved in the design, manufacture, and construction/installation of the feature of work were available and willing to be interviewed; and (ii) the feature presented a particular WHS challenge for construction. These criteria were established to provide completeness of data and to ensure that project participants would directly consider the WHS hazards/risks associated with the construction of the feature and make explicit decisions about how WHS hazards/risks would be controlled in each case. Multiple features of work (i.e, cases) were selected from a number of construction projects involved in the research. The total number of cases in the analysis was 23. The number of cases from each construction projects ranged between 1 and 4 and the mean number was 2.3. Owing to the intensity of data collection and the availability of project personnel, of these 23 cases, complete social network data could only be collected for 13 cases.

Data collection

Data were collected by conducting interviews with project participants involved in the planning, design and construction of the selected features of work. A total of 185 interviews were conducted. The average number of interviews per case was 8.04.

Initially interviews were conducted with key project participants, i.e, the client, the principal design consultant and the construction contractors were interviewed. From these interviews, other actors in the network were identified. These 'leads' were followed up if certain criteria were met. These criteria mirror those used by Pryke (2005), namely that (i) the individual was an employee of one of the project actor firms comprising the project coalition and was actively engaged in the project at the time that the data was gathered, and (ii) the link between the individual at least one other actor in the network was significant in terms of frequency and perceived importance of input by other actors. This process of sampling continued until no new leads were identified in actors' interviews. Data were verified by confirming the existence of each network link with both actors. Thus, at least two actors had to confirm that a link between them existed for it to be included in the social network analysis.

All participants were asked to rate the frequency of their communication during pre-construction project decision-making with each other actor. This rating was based on a five point Likert scale ranging from 1 (occasionally) to 5 (daily).

Independent variables

Two independent variables were measured, i.e, network density and the degree centrality of the constructor. Network density expresses the ratio of actual links or relationships in a network to the maximum possible number of links the network could have (Borgatti and Everett, 2006). Thus, as more proportionally more actors are connected to each other, the density value increases. Degree centrality refers to the extent to which an actor (a node in the network) is connected to other actors (or nodes). Thus, for each actor, the degree centrality is the ratio of the number of relationships the actor has relative to the maximum possible number of relationships that the actor could have. This measure of centrality provides a measure of an actor's communication activity within the network such that if an actor possesses high degree centrality then this indicates that they are highly involved in communication within the network relative to other actors. Pryke (2005) argues that compared to other measures of centrality (e.g. betweenness and closeness), degree centrality is a useful indicator of an actor's power within the network.

Degree centrality can be measured by combining the number of lines of communication into and out of a node in the network (see, for example, Alsamadani et al., 2013). The former is referred to as in-degree centrality while the latter is referred to as out-degree centrality. However, in this research we chose to measure the constructors' *outgoing* communication only. This was a deliberate choice because the research aimed to measure the extent to which construction process knowledge is considered and used in pre-construction (planning and design) decision-making and the implications that this has for the quality of WHS risk control. The construction contractors' out-degree centrality was therefore used as a proxy measure of the extent to which construction process knowledge was available to pre-construction stage decision makers.

Dependent variable

The dependent variable of interest was the quality of risk control solutions implemented during the construction stage of the project. For each feature of work (i.e, case) in the sample, WHS risks were identified. A common categorization scheme was developed based on the National Institute for Occupational Safety and Health (NIOSH) Occupational Injury & Illness Classification System (OIICS) (BLS, 2012). WHS risks relevant to each case were identified and categorized using this classification system (e.g., fall, slip, trip; struck by object or equipment, etc.).

Once WHS risks had been classified for each case, the methods by which each risk was actually controlled were identified. This information was elicited during the interviews and supplemented with site-based observations and examination of project documentation (e.g. plans and drawings). Thus, an attempt was made to verify the information provided during the interviews with on-site observation.

Methods of WHS risk control were classified according to their type. This classification was based on the hierarchy of control (HOC). The hierarchy of control (HOC) is a well-established framework in WHS (see, for example, Manuele, 2006). The HOC classifies ways of dealing with WHS hazards/risks according to the level of effectiveness of the control. At the top of the HOC is the elimination of a hazard/risk altogether. This is the most effective form of control because the physical removal of the hazard/risk from the work environment means that workers are not exposed to it. The second level of control is substitution. This involves replacing something that produces a hazard with something less hazardous. At the third level in the HOC are engineering controls, which isolate people from hazards. The top three levels of control (i.e, elimination, substitution and engineering) are technological because they act on changing the physical work environment. Beneath the technological controls, level four controls are administrative in nature, such as developing safe work procedures or implementing a job rotation scheme to limit exposure. At the bottom of the hierarchy at level five is personal protective equipment (PPE) – the lowest form of control. Although, much emphasized and visible on a worksite, at best, PPE should be seen as a "last resort," see, for example Lombardi et al.'s analysis of barriers to the use of eye protection (Lombardi et al. 2009). The bottom two levels in the HOC represent behavioural controls that eek to change the way people work (for a summary of the limitations of these controls see Hopkins, 2006).

To ensure consistent classification of the WHS risk control measures, a detailed coding framework was developed. This coding framework identified the options available for controlling various WHS risks and provided the HOC score that should be given for each risk control option. The coding framework was used by two researchers who independently coded the data.

An average HOC score was generated for each feature of work, reflecting the quality of risk control solutions implemented for identified WHS hazards/risks. Each level of the HOC was given a rating ranging from one (personal protective equipment) to five (elimination). The risk controls implemented for hazards/risks presented by each feature of work were assigned a score on this five point scale. In the event that no risk controls were implemented, a value of zero was assigned. Using these values the mean HOC score for each feature of work was generated. Thus, if two hazards were identified, one was eliminated and the other controlled by administrative methods, the mean score would be 3.5.

Inter-rater reliability

To ensure that the coding of WHS risk control measures was consistent an inter-rater reliability assessment was performed. A list of WHS hazards and risk controls was sent to an international construction WHS research group based in the United States. The US research group rated the Australian case data using the HOC classification method. The US raters' HOC classification was consistent with the Australian research team classifications in 12 of 14 Australian cases included in the reliability check (85.7%). This suggests an acceptable level of inter-rater reliability.

Data analysis

In the first instance data were entered into the UCINET social network analysis software. Sociograms were developed for each case (feature of work). Network density was calculated for each feature of work at the pre-construction phase as well as for the overall case (by calculating the ratio of existing information ties to the maximum number of possible ties in the network). Next the constructor's out degree-centrality in each network was calculated by summing the information tie values linking constructor to other stakeholders in a network. To facilitate the comparison between different features of work, the constructor's degree-centrality value in each network was normalised by dividing it into the maximum possible tie value in that network. The constructor's normalised degree-centrality was calculated for each feature of work at the pre-construction (i.e, planning and design) stage of the project, as well as for the overall case.

The 13 cases for which social network data was available were divided into three groups:
1) cases for which the HOC score was lower than one standard deviation below the mean,
2) cases for which the HOC score was higher than one standard deviation above the mean, and
3) cases for which the HOC score was between one standard deviation below the mean and one standard deviation above the mean.
Three cases fell into the higher than average HOC group and three fell into the lower than average HOC group. Independent samples t-tests were conducted to compare the density and centrality values for cases in which the HOC score was above average and those for which it was below average.

Results

Quality of risk control

The quality of WHS risk control solutions implemented was rated for all 23 cases in the analysis. The results of these ratings are presented in Table 1.

Table 1: Summary of cases and HOC scores

Project	Case/Feature of work	Mean HOC
Centrifuge replacement for sewerage treatment facility	Installation of centrifuge	4.08
	Pipe works	3.73
	Installation of a steel platform	2.44
Theatre demolition	Demolition	3.08
Public space landscaping	Landscaping	3.05
42-story residential complex	Construction/installation of façade	4.25
	Construction of internal stair egress	3.33
Manufacturing facility	Roof and wall cladding	2.60
	Erecting/Installation of roof structure	4.50
	Erection/installation of steel columns	4.20
	Construction of foundation system	4.50
Food processing plant reconstruction	Steel columns	3.56
	Sewerage disposal system	3.61
	Fire wall	2.63
Cemetery mausoleum	Construction of basement mausoleum	4.19
Suburban train station	Construction of reinforced concrete columns	4.63
	Construction of ramp access	3.50
	Construction of platform and supporting columns	4.31
Water pumping station upgrade	Construction of wet well	3.50
	Construction of valve chamber	4.00
Flood recovery works	Construction of a retaining wall	2.73
	Construction of a retaining wall	4.25
	Rectification of a pedestrian bridge	4.25

The mean HOC score for all 23 cases was 3.69 (SD=0.67). The maximum HOC score was 4.63 and the minimum was 2.44.

These scores did not differ greatly from the 13 cases for which social network analysis data were available. The mean HOC score for the cases for which social network analysis data were collected was 3.84 (SD=0.65). The maximum HOC score for cases for which social network data were collected was 4.63 and the minimum was 2.30.

Project network metrics

Table 2 presents descriptive statistics for the 13 cases for which complete social network data was available.

Table 2: Descriptive statistics for social network characteristics (N=13 cases)

	N	Minimum	Maximum	Mean	Std. Deviation
Pre-Construction Normalized Degree Centrality	13	1.76	24.81	11.33	7.10
Overall Normalized Degree Centrality	13	3.33	23.33	13.09	6.62
Pre-Construction Network Density	13	.074	.63	.27	.18
Overall Network Density (Whole Prj)	13	.119	.61	.28	.15

The extent of the construction contractors' out degree centrality varied considerably between cases. The average score was 11.33 (SD=7.10). The construction frequency with which the construction contractor engaged in outward communication with other parties in the project network varied considerably. The average out degree centrality score was score was 11.33 (SD=7.10) in pre-construction project stages and 13.09 (SD = 6.62) for the entire project period. The average network density values were 0.27 (SD=0.18) in pre-construction stages, and 0.61 (SD=0.28) for the entire project period.

Relationship between project network characteristics and risk control outcomes

Table 3 shows the results of the comparison of mean social network values between cases with the highest and lowest HOC scores.

Network density was higher in cases with more positive HOC outcomes. This was the case for overall project network density and network density measured only in the pre-construction (i.e, planning and design) stage of the project. However, the independent samples t-tests revealed that the difference in network density among cases with high compared to low HOC values was not statistically significant.

Constructors' out degree centrality was higher in cases with more positive HOC outcomes. This was the case for the constructor's degree centrality measured across the project as a whole, as well as the constructor's degree centrality relating to only the pre-construction (i.e, planning and design) stage. In both cases, the independent samples t-tests revealed these differences to be statistically significant.

Table 3: Comparison of cases with lower versus higher than average HOC scores

Variable	HOC grouping	Mean	T value	Degrees of freedom	Significance (*p*)
Project network density (pre-construction stage)	High HOC	0.268	-1.231	3.206	NS
	Low HOC	0.149			
Constructor’s normalised degree centrality (pre-construction stage)	High HOC	14.193	-3.636	2.071	0.065
	Low HOC	5.377			
Project network density (whole project)	High HOC	0.168	-1.535	3.085	NS
	Low HOC	0.286			
Constructor’s normalised degree centrality (whole project)	High HOC	16.080	-3.148	3.886	0.036
	Low HOC	9.103			

NB: Cases with High HOC scores are those for which HOC > mean +1 standard deviation, cases with low average HOC scores are those for which HOC < mean -1 standard deviation.

Example cases

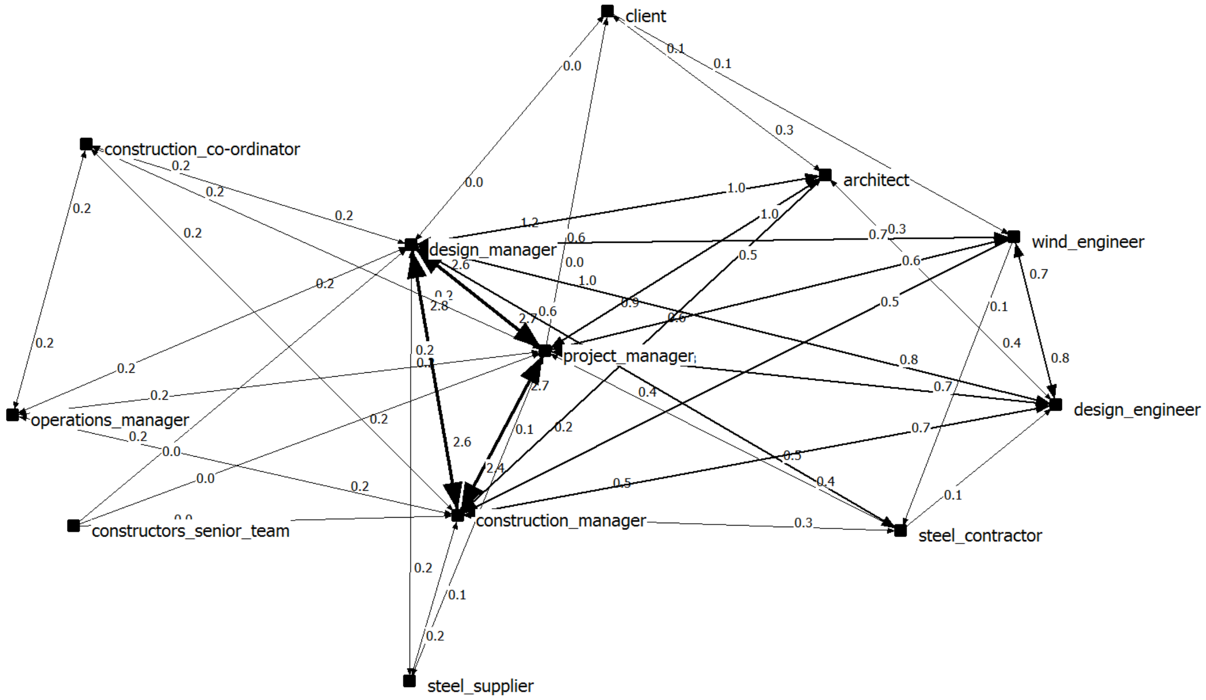
The statistical comparisons provide some insight into the relationship between characteristics of the social network and the quality of risk control solutions implemented. However, this statistical analysis does not explain how or why a constructors’ position or level of activity within a communication network shaped HOC outcomes. Two cases representing different social network configurations are described below, with reference to the sociograms produced for each case. These cases provide insight into the way in which the constructors’ outgoing communication (particularly during the pre-construction stages) contributed to WHS risk control outcomes during construction.

Case example 1 – high rise building façade system

Figure 1 shows the sociogram relating to the planning and design of a self-supporting, architectural façade to be connected to the exterior of a 42-story building.

Twelve key project participants were identified for this case. The project used a design and construct delivery method in which the preliminary building design was completed by the client’s architects and specialist consultants. The tender documents indicated the façade was constructed of light-weight frame structure made of glass reinforced concrete (GRC) with larger vertical sections made of pre-cast reinforced concrete. During the tender process, the contractor raised concerns about the structural adequacy of the GRC frame for a building of this height.

Figure 1: Example communication network for a building façade element



NB: numbers denote the frequency of outgoing communication between project participants before the commencement of construction work (1= occasionally, 5= daily).

Following the engagement of the design and construction contractor, structural and constructability reviews were conducted to investigate design options and material. A decision was made to use rolled steel sections instead of GRC elements. Consequently, the façade members and connections were re-designed. Using much lighter steel elements reduced material handling and exposure to ergonomic hazards. It also eliminated the risk of the façade structure collapsing during or after construction.

The constructor proposed off-site manufacture of the façade. In this way, the construction process would be quicker and eliminating the need to store materials reduced congestion on the small inner-city construction site. The off-site manufacture of the façade reduced exposure to the risk of contact with objects and equipment and reduced the risk of falls, slips, and trips.

In the original planned sequence of work, the façade frame was to be fitted off once the building structure was completed. However, the constructor suggested an alternative sequence in which façade elements were to be fitted floor by floor as the building was being vertically constructed. This eliminated the need to work from swing stages or other mechanical equipment on the outside of the building. Workers were able to install and connect the framing beams from the safety of a finished floor level.

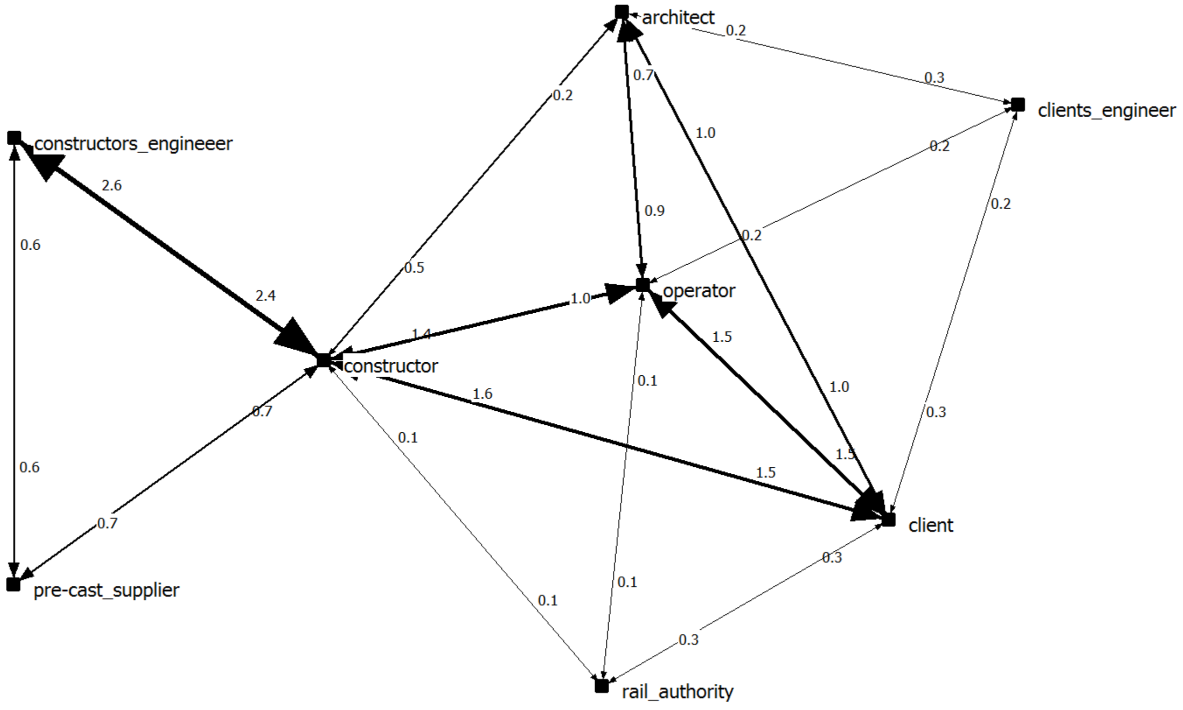
The sociogram shows a high level of connectivity with a lot of direct information ties among the actors. This indicates a fast and easy information exchange pattern in the network.

The social network data also reveals a medium normalized degree-centrality for the constructor. However, the sociogram reveals high frequency of information exchange among the construction manager, the design manager and the project manager. These actors arguably had the most important decision making roles in the redesign of the façade and development of the construction/installation sequence. The network shows that these three actors form a triangle characterized with particularly strong ties (indicated by the thickness of the connecting lines) in the core of the network. This suggests a high level of design and construction information exchange occurred among these actors at the pre-construction stage. The network also reveals some important connections between the three core actors and subcontractors/suppliers, suggesting the involvement of the subcontractors in decisions concerning the design and planning of the façade.

Case 2 – bridge column construction

Figure 2 shows the sociogram relating to the planning and design of supporting columns for a pedestrian bridge spanning the railway lines at a new suburban train station. Eight prominent project participants were identified for this case. The original concept plan for the station involved the construction of a new 'island' platform, built between two existing and fully functioning rail lines. The footbridge would provide access to the platform from either side of the tracks.

Figure 2: Example communication network for bridge columns



NB: numbers denote the frequency of outgoing communication between project participants before the commencement of construction work (1= occasionally, 5= daily).

The project used a design and construct delivery method in which the preliminary bridge design was carried out by an engineering consultant engaged directly by the client. This design comprised a walkway which was to be supported by reinforced walls at each end and three columns in-between. As part of the tender submission the Design and Construction contractor proposed that the number of columns be reduced to two. Eliminating one of the piers would mean that the constructor would be able to reduce the amount of construction work in the railway corridor (a designated area either side of the tracks). Reducing the amount of work within the railway corridor significantly reduced risks associated with train movements and overhead power supply lines. It also increased the separation between construction activities and rail tracks providing more space for crane movement and lifting operations.

The constructor also decided to construct the columns in-situ, in three sections using a modular design approach. The first section of the column would be built using standard construction methods, whereby formwork and steel reinforcement bars would be installed, the structure propped and concrete poured. Once the first section was completed it would be used to 'fix and stiffen' the formwork for the next stage. The formwork would be clamped to the completed section and extend up to allow the next three metres of concrete to be poured. This process was repeated until the column reached the required height. Using slip-forms with z-bars to tie the formwork together the constructor was able to eliminate propping of the top two stages of the column. The only section that needed to be propped was the first stage of the column. Working at height issues and manual handling hazards associated with in-situ construction were significantly reduced through the use of steel reinforcement "cages" that could be fabricated at ground level and lifted into position using a crane. The crane was also used to help fit and 'slip' the formwork shutters up the column.

The network pattern shows a high level of connectivity for the constructor with direct information ties between the constructor and almost all the other actors in the network. This suggests a smooth and effective information exchange between the constructor and other stakeholders at early stage of the project.

Given the high risk nature of the project and the specialist knowledge required to undertake the construction work safely, the contractor managed to maintain a high level of health and safety performance through involving the client, the rail authority and the transport operator in decision making process. This is evident by the relatively high frequency of communication between the constructor and these stakeholders.

On the right hand side of the sociogram are key "demand-side" stakeholders with high regulatory/authority power (client, rail authority, transport operator). Due to the nature of the project and the requirement to maintain the transport operations during the construction phase, the constructor needed to obtain permits to work to ensure all required safety controls were in place. Communication links between the constructor and the client and rail authorities were therefore critical. On the left side of the network are key "supply –side" stakeholders, who had a significant role in shaping decisions about the use of the modular construction systems which contributed to the reduction of WHS risks in the project.

The design and construction contractor is the central actor connecting these two groups. In this central position, the contractor was able to identify constructability issues early in the project and drive the re-design of various components, including the bridge columns.

Discussion

Construction involvement in project planning and design decision-making

The research sought to examine whether the position of construction contractors in project communication networks is related to the quality of measures implemented to control WHS risks.

The results provides preliminary empirical evidence to indicate that the involvement of constructors in project decision-making (including decision-making that occurs before the commencement of construction) is linked to the adoption of "higher order" WHS risk controls.

The t-tests revealed a significant difference in the constructors' out-degree centrality values among cases with above and below average HOC scores. While these findings do not indicate a causal relationship, they do suggest that knowledge about construction processes and methods may an important and valuable resource that facilitates the adoption of high-quality risk control outcomes in construction projects. Constructors are responsible for the actual construction operations in a project and thus have a strong motivation and interest in ensuring work can be performed with minimal risk to health and safety (Song et al. 2009). Compared to other project participants, constructors have a high level of construction expertise because of their specialized training and knowledge and experience in the application of construction materials and methods. Constructors are therefore able to provide advice about WHS hazards/risks and ways to mitigate them in construction activities. When this information is fed into "upstream" decision-making, i.e, during the planning and design stages of a project, it may be particularly useful. Indeed, strategies to elicit constructors' process knowledge during the early stages of a construction project are likely to improve the effectiveness if safety in design activities and facilitate the adoption of technological (rather than behavioural) controls for WHS risk.

The qualitative case descriptions further illustrate the potential WHS benefits that can flow from frequent communication between the constructor and other project participants in communications networks early in the project life-cycle. In the case of the façade the contractor made significant changes to the materials and methods used to construct the façade, both of which significantly reduced WHS risks. In the case of the pedestrian bridge the contractor was able to reduce WHS risk by reducing the number of columns required to support the bridge span and adopting a modular design and construction method.

Information exchange network characteristics

In our analysis, the constructor's out degree centrality was associated with the selection of higher order controls for WHS risks. However, the density of a communications network did not differ significantly between cases exhibiting high, compared to low HOC scores. This finding is in contrast to the results obtained by Alsamadani et al. (2013). In their analysis of safety communication in construction work crews Alsamadani et al. (2013) report network density (but not centrality) to be related to higher levels of WHS performance. Reasons for this difference are unclear. However, Alsamadani et al. investigated communication networks within small construction work crews. In this context the centrality of team members is possibly less important than the extent to which all group members communicate with one another about safety. Our research was specifically focused on the extent to which the actors with construction and/or WHS knowledge shared information with other members of a multi-disciplinary team. In this context the overall network density is likely to be less important than the degree centrality of the constructor. However the different findings highlight the need to exercise care and be conceptually clear in the formulation and testing of hypotheses about social network characteristics and WHS outcomes.

Integrating mechanisms

Styhre and Gluch (2010) describe how knowledge stocks in construction projects reside within organizations that form a project coalition. They suggest that bridging mechanisms can help to ensure that organizational interflows of knowledge occur. Our results suggest that specific provision of mechanisms to ensure that constructors' knowledge can be accessed might yield positive WHS benefits. Consistent with this view, Hare *et al*. (2006) report that two-way communication between designers and constructors, the early involvement of the constructor, participation in health and safety workshops and collaborative brainstorming are important mechanisms to support the integration of WHS into project planning and design decision-making. It is important to note that some important construction/WHS knowledge may reside with specialty subcontractors. Franz et al. (2013) present comparative case study data to suggest that early involvement of specialist contractors produces better WHS outcomes in otherwise comparable projects. Integrating mechanisms should seek to access this knowledge. Opportunities to engage participants with in-depth construction process knowledge early in the life of a project and actively elicit their suggestions for effective ways to eliminate (where possible) or reduce WHS risks are recommended. The input of construction process knowledge could be sought using face to face interviews, meetings or workshops, or by developing web-based knowledge-based systems (see, for example, Cooke et al. 2008).

Social network analysis as a practical tool

The research demonstrates that social network analysis can be used to quantify and compare project communication networks. Given the significant link between the constructors' out degree centrality and the quality of WHS risk control, the analysis of project communication networks could help organisations to improve the integration of WHS into project decision-making (particularly in the pre-construction stages). The measurement of project communication networks could also be useful in benchmarking within project organizations (see also Alsamadani et al., 2013).

Social network analysis may also be a useful tool for the analysis and identification of network "gaps' (El-Sheikh and Pryke, 2010). Used in this way, social network analysis could be used to diagnose network problems and identify opportunities for increasing information exchange to support WHS improvement. In particular, social network analysis is likely to be particularly useful in understanding the pattern of inter-organizational relationships and information exchanges that are important to ensuring that WHS is integrated through the activities of the construction supply chain.

The hierarchy of control

The research also reveals the usefulness of using the hierarchy of control as a measure of project WHS performance. The use of injury rates as a dependent variable in WHS research has been questioned due to their poor reliability and high levels of under-reporting (Lingard et al. 2013). For example, in the United Kingdom, Daniels and Marlow (2005) found that the reporting of non-fatal construction injuries is as low as 46%. Alternative, more reliable measures of WHS performance have been recommended. In particular, the use of "leading" indicators of WHS performance is advocated. Leading indicators measure the state of WHS before the emergence of WHS risk rather than after the occurrence of undesirable events. As such, they are a more direct measure of WHS than accidents. The research suggests that classifying risk controls using the HOC may be a more proactive (and reliable) way to measure WHS in construction projects. Used in this way, the HOC can provide a practical measure of the quality of the WHS effort, rather than an after-the-fact measure of things that have already gone wrong.

Conclusions

The research sought to measure the quality of WHS risk controls implemented in construction projects and determine whether the quality of WHS risk control outcomes is associated with the position and role of the construction contractor in project communication networks. Social network analysis was used to quantify two dimensions of the communications network (i.e, network density and the constructors' out degree centrality). The construction contractors' out degree centrality was used as a proxy measure of the extent to which decisions were informed by knowledge of construction processes and methods. The quality of WHS risk control was measured using an innovative classification system based on the theoretical hierarchy of control (HOC).

The results revealed that in cases in which the quality of WHS risk controls was higher than average the construction contractor's out degree centrality was significantly higher than in cases in which the quality of risk controls was lower than average. This provides a prima facie case for the establishment and maintenance of strong communication between contractors and other project participants. In particular, the opportunity to seek the input of construction contractors into decision-making during the planning and design stages is recommended as a way to facilitate the adoption of technological (as opposed to behavioural) controls for WHS risk.

The findings have implications for improved practice in the management of WHS in construction projects, in which the traditional separation between design and construction has been identified as a barrier to the effective implementation of safety in design. Arguably the greatest opportunity to implement technological controls for WHS risk, i.e, those that eliminate or reduce a risk by adopting engineering solutions, is during the early project planning and design stages. The research suggests that realising these "high order" technological risk controls is more likely when the construction contractor has a central and active role in project communication networks before construction commences.

Limitations and future research

The research was limited in a number of respects. These have important implications for the development of theory pertaining to the influence of communication between project team members on WHS outcomes. Firstly, the measurement of the construction contractors' out degree centrality only quantified the frequency of outgoing communication. No attempt was made to evaluate the quality or content of the communication. It is possible that the relationship between construction contractors' out degree centrality and the quality of risk control outcomes will be moderated by the quality of communication. Thus, when valuable information is communicated and when other project participants receive and respond to this communication in a positive way, the relationship between the constructors' out-degree centrality and the quality of risk control outcomes may be strong and positive. However, when communication is about relatively trivial matters and/or if other project participants fail to respond to this communication, then the relationship between the constructors' out-degree centrality and the quality of risk control outcomes may be non-significant (or even negative). Further research using hierarchical regression modelling techniques could test for a moderating effect and is recommended. However, a larger sample size would be required than was achieved in the reported research. The research was also limited by focusing solely on the out-degree centrality of the constructor. Future research should examine the WHS influence of the position and activity of other network participants within projects. Notwithstanding these limitations, the research has provided some empirical evidence to link the extent of inter-organizational communication with WHS outcomes in construction projects.

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