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Construction Hazard Prevention: The Need to Integrate Process Knowledge into Product Design

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Social network analysis was used to model information exchange networks in construction case studies in the United States of America and Australia/New Zealand. For each case, the quality of occupational safety and health (OSH) 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. The construction contractors' degree centrality was examined as a proxy measure of the constructors' influence in decision making during the pre-construction stages of the project. 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' degree centrality for cases with high and low risk control efficacy scores. Constructors had significantly higher degree centrality in cases with high compared to low quality OSH risk control outcomes. The results provide preliminary evidence that integrating construction process knowledge into pre-construction decision-making produces better OSH outcomes. The research also highlights the potential usefulness of social network analysis and network metrics in OSH performance measurement and benchmarking.

Key Words: Occupational Safety and Health, Prevention through Design, Risk Control, Knowledge Integration, Education

Introduction

Prevention through Design (PtD)

The practice of anticipating and 'designing out' potential occupational safety and health (OSH) hazards associated with processes, structures and plant and equipment (referred to in this paper as Prevention through Design or PtD) has attracted considerable attention in recent years (Schulte, 2008). In 1992 the Council of European Communities implemented the Directive 92/57/EEC – concerning temporary or mobile construction sites. This directive required consideration of construction workers' OSH during the design stage of construction projects. The United Kingdom responded to the Directive with the enactment of the *Construction (Design and Management) Regulations* in 1994 (which were revised in 2007 and are currently undergoing further review and revision). Interest in PtD in construction also spread to countries outside the European Union. In Australia legislation requiring designers of buildings and structures to consider workers' OSH has been implemented in all jurisdictions. In the United States of

America, PtD is a strategic goal cited in the *National Construction Agenda for Occupational Safety and Health in the US Construction Sector* (NORA Construction Sector Council, 2008).

Implementation problems

However, commentators have identified significant implementation issues relating to PtD in the construction industry. For example, Atkinson and Westall (2010) note that many widely-cited PtD solutions, such as designing anchorage points for fall arrest devices in structures and providing guard-rails do not eliminate an inherently dangerous activity, i.e, working at height. They suggest that these PtD measures produce a modest reduction in OSH risk experienced by workers but fall short of optimizing the reduction of risk. Researchers also comment that design professionals in the construction industry (architects and engineers) possess limited knowledge of construction processes (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).

Construction projects are traditionally structured in such a way as to produce a temporal and organizational segregation between the design and construction functions. This can impede the development of shared project goals (Baiden and Price, 2011) and can negatively impact project outcomes, including those relating to OSH (Love and Gunasekaran, 1998). Even in more integrated Design and Construct projects, the design of the product to be constructed is often outsourced to a specialist team of professional designers and positive OSH outcomes are not guaranteed (Atkinson and Westall, 2010). 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).

Aim

The research aimed to investigate the extent to which the integration of construction process knowledge into decision-making about the permanent design of a facility can improve OSH risk control outcomes. The research:

- Investigated the quality of OSH risk control outcomes in case study projects,
- Measured the prominence of the construction contractor in project social networks, and
- Compared the construction contractor's prominence in cases with high quality and lower quality OSH risk control outcomes.

Research Methods

Case study design

The research adopted a comparative case study approach (Yin, 1994). Data were collected from a total of 23 construction projects, 10 in Australia/New Zealand and 13 in the United States of America. For each project, features of work were purposefully identified by project participants in consultation with the research team. Features of work were selected because they presented a particular health and safety problem or challenge.

For each feature of work, comprehensive data was collected to capture decisions that were made in relation to the design of the feature of work, the process by which it was to be constructed and the way that health and safety hazards were to be addressed. Data were collected by conducting in-depth interviews with stakeholders involved in the planning, design and construction of the selected features of work. These interviews explored the timing and sequence of key decisions about each feature of work, and the influences that were at play as these decisions 'unfolded' in the project context. During the course of the research 288 interviews were conducted (185 in Australia and 103 in the USA). The average number of interviews per feature of work was 6.7.

Dependent variable

Data was collected about OSH hazards and the risk control solutions implemented within the case examples. This data was elicited during the interviews and supplemented with site-based observations and examination of project documentation (e.g. plans and drawings). For each feature of work, a score was generated reflecting the quality of implemented risk control solutions. This score was based on the hierarchy of control (HOC).

The hierarchy of control (HOC) is a well-established framework in OSH (see, for example, Manuele, 2006). The HOC classifies ways of dealing with OSH 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 they seek to change the way people work (for a summary of the limitations of these controls see Hopkins, 2006).

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.

Independent variable

Social network analysis (SNA) was used to map the social relations between participants involved in making design decisions about each feature of work. SNA is an analytical tool to study the exchange of resources between participants in a social network. Using social network analysis, patterns of social relations 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, participants are represented as nodes. To varying extents, these nodes are connected by links which represent the relationships between participants in the network.

SNA has been recommended as a useful method for understanding and quantifying the roles and relationships between construction project participants (Pryke, 2004; Chinowsky et al. 2008). The technique has been used to analyse knowledge flows between professional contributors to project decision-making (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 SNA to investigate the relationship between safety communication patterns and OSH performance in construction work crews.

In order to gauge the construction contractor's prominence in a project social network, the contractor's degree centrality was calculated. Degree centrality refers to the extent to which one participant is connected to other participants in a network. Thus, degree centrality is the ratio of the number of relationships the actor has relative to the maximum possible number of relationships that the network participant could have. If a network participant possesses high degree centrality then they are highly involved in communication within the network relative to others. Pryke (2005) argues that degree centrality is a useful indicator of power and influence within a 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). This presents an aggregate value representing the participant's communication activity. However, the independent variable used in this research was calculated using only the construction contractors' outgoing communication. This was a deliberate choice because the research aim was to investigate whether OSH risk control is of a higher quality when project decisions are made with due consideration of construction process knowledge. Thus, the flow of communication from the construction contractor to other network members was deemed to be of greater relevance that the volume of information they received.

Results

The sample

Multiple features of work were selected from each construction project and the total number of features of work in the analysis was 43. The number of features of work from each construction projects ranged between 1 and 4 and the mean number was 1.9.

Features of work were drawn from the heavy engineering (39.6%), commercial (20.9%), industrial (27.9%) and residential (11.6%) sectors of the construction industry. The majority of cases were collected in projects procured using a Design and Build delivery mechanism (34.9%). Twelve cases (27.9%) were collected in accelerated project delivery arrangements. Nine cases (20.9%) were drawn from projects procured using a traditional (Design-Bid-Build) delivery method and seven cases (16.3%) were collected in projects using a collaborative delivery method.

Inter-rater reliability

To ensure that the coding of OSH risk control measures was consistent between the US and the Australian research teams, an inter-rater reliability assessment was performed. A list of OSH hazards and risk controls from one case were sent from the Australian to the US research team (and vice versa). Each group then rated the others' sample 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 (85.7%). The Australian raters' HOC classification was consistent with the US research team classifications in 9 of the 10 US cases (90%). The high level of agreement suggests that the HOC classification method was applied consistently between the two countries.

Comparison of means

Table 1 shows the mean HOC scores for cases by industry sector, project type and country. Australian cases in the analysis had higher average HOC scores than were evident in the US cases. Further, the difference between mean HOC scores between the US and Australian cases was found to be statistically significant (t=7.731, p=.000). Cases drawn from collaborative or design and build projects had slightly higher HOC scores than cases drawn from accelerated (fast track) or design-bid-build projects. Cases drawn from the commercial and residential sectors had lower mean HOC scores than cases drawn from the engineering and industrial construction sectors. However the differences in HOC scores did not differ significantly by delivery method or industry sector.

Table 1: Mean HOC scores by country, project delivery method and industry sector

Case descriptor	**Mean HOC score**	**Standard deviation**
Country		
United States	2.48	.311
Australia	3.69	.671
Delivery method		
Collaborative	3.36	.632
Accelerated	2.98	.820
Design-bid-build	2.71	.602
Design and Build	3.38	.233
Sector		
Heavy engineering	3.33	.844
Residential	3.02	.777
Commercial	2.72	.649
Industrial	3.13	.807

Table 2 shows the results of the comparison of mean social network values between cases with the highest and lowest HOC scores.

Constructors' 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 2: Comparison of cases with low versus high HOC mean scores

Variable	**HOC grouping**	**Mean**	**t**	**Significance (*p*)**
	Low HOC	.149		
Constructor's normalised degree centrality (pre-construction stage)	High HOC	14.193	3.636	.022
	Low HOC	5.377		
	Low HOC	.168		
Constructor's normalised degree centrality (whole project)	High HOC	16.080	3.148	.035
	Low HOC	9.103		

Case example: Design and construction of steel columns and roof structure at a food processing and storage facility

An initial concept design was developed on behalf of the client to accommodate operational requirements for the facility. The concept design included a steel framed structure consisting of three spine trusses supported by five rows of steel columns. To maximise useable floor space, the columns were positioned in the middle of product stacks rather than at the ends of the rows.

The Design and Construction contractor suggested eliminating one row of columns. This design alternative required fewer columns to be lifted and manoeuvred into place, reducing the duration of exposure to OSH risks associated with lifting operations. The contractor also suggested revisions to the roof design, suggesting the use of trussed rafters connecting to the main spine trusses instead of using steel beams as rafters. The fabrication of rafter trusses was slightly more expensive, but these trusses weighed less than steel beams and could be manufactured off-site. The reduced weight of the roof enabled the use of smaller sections for supporting columns. It also made the erection and installation of the roof quicker and easier.

All supporting columns were fitted with a bearing plate allowing trusses to be temporarily supported while connections at each end were bolted. This reduced the need for propping and manual handling associated with installing and dismantling props and also freed the area around the columns and under the trusses of any obstacles or trip hazards that may have been caused by props. At the same time, this design solution reduced the extent of work required at height to connect the trusses to the columns and reduced the OSH issues associated with suspended loads. As the client's engineer commented:

> *"[The constructor has] got quite a good, what I call a bearing type detail, so you can actually put the trusses up and have them take the gravity load away before you start trying to put the bolts in. And that's one of the major concerns [on another similar project] is that we should have picked it up when we did the structural check, but of course we just checked the structure rather than checking the buildability."*

The structure was designed so that erection could be done in self-supporting sections. This allowed the builders to start at one end of the building and move progressively along the length of the building. Using this method, the constructor was able to ensure that crane lifts were within safe reach tolerances, without having to extend the cranes arm over already constructed portions of the structure. To ensure the constructability of the facility before the start of construction work, the main constructor involved subcontractors in reviewing the design and erection/installation sequences. The resulting PtD solutions resulted in an HOC score of 4.2.

Figure 1 shows the pre-construction social network for this project. The data revealed a relatively high normalized degree-centrality (14.46) for the constructor. As the sociogram depicts, the construction contractor had direct links with the majority of other network participants. The network pattern shows that the constructor took advantage of direct information ties with suppliers and sub-contractors (steel erectors and concreters). These suppliers/subcontractors possess practical knowledge about constructability issues and would be responsible for executing the construction tasks. Their engagement in decision making enabled the constructor to benefit from their specialised knowledge in proposing practical and safer design solutions which, in turn, improved the quality of OSH risk control.

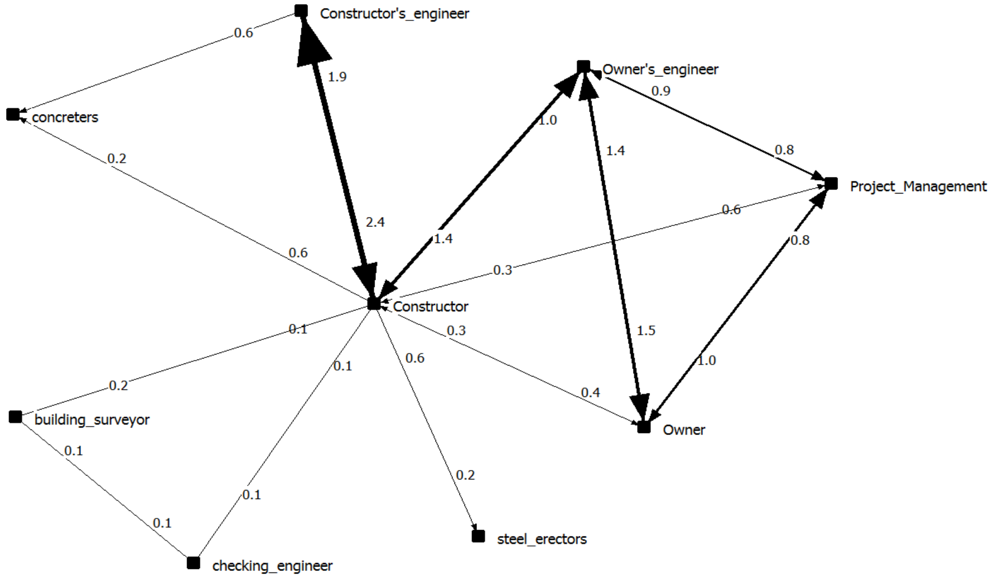

Figure 1: Sociogram for the steel structure design at a food processing and storage facility

On the right hand side of the sociogram are key "demand-side" stakeholders, including the owner, owners' engineer and project manager. On the left side of the network are key "supply –side" stakeholders, including the concretors and steel erectors. Also to the left of the network are stakeholders who supply design related information and services to the network (i.e, the checking engineer and building surveyor). The Design and Construction contractor is the central actor connecting these three groups. In this central position, the contractor was able to identify constructability issues before construction commenced and drive the redesign of various components, which still met the owner's operational requirements for the facility and complied with regulatory requirements.

Discussion

The importance of construction process knowledge

The research provides preliminary empirical evidence that the integration of construction process knowledge in design decision-making, as evidenced by information flowing from the construction contractor to other project participants, is linked to the adoption of more effective OSH risk control solutions.

The t-tests revealed a significant difference in the constructors' degree centrality values between cases with above and below average HOC scores. These findings do not indicate a causal relationship, but do suggest that knowledge of construction processes is an important and valuable resource that can support the adoption of preferred technological controls for OSH risks. Compared to other project participants, construction contractors have a high level of construction expertise because of their specialized training and experience in the application of construction materials and methods. Constructors are arguably in the best position to provide advice about OSH hazards/risks and ways to mitigate them in construction activities. Construction contractors are also responsible for construction operations and have a strong motivation and interest in ensuring work can be performed with minimal risk to OSH (Song et al. 2009).

Integrating mechanisms

The results highlight the potential OSH benefit to be gained by integrating construction process knowledge into the design of facilities to be constructed. Unfortunately the fragmented and sequential nature of design and construction work inherent in construction projects militates against this integration. Integrated project delivery methods may increase the extent that process knowledge is used to inform product design in construction projects. However, the fact that no significant differences were found between the HOC scores for cases drawn from projects procured in different ways suggests that collaborative forms of project delivery do not guarantee better OSH outcomes will be realized. There is also potential to improve OSH outcomes through the adoption of concurrent engineering (CE). CE is characterised by a unified development process and a multidisciplinary project delivery team and has been proposed as a technique to improve construction productivity (Love and Gunasekaren, 1997). Another key feature of CE is the concurrency or overlapping of activities. The integration of product and process design has been recommended as a means to improve construction project performance (Anumba et al. 2000). The research results suggest that simultaneous consideration of product and process design could produce significant improvement in the quality of ways in which OSH risks are controlled.

Implications for education

The research has important implications for the education of construction industry professionals, particularly those involved in “upstream” decision-making. Design professionals’ low levels of process knowledge has been cited as a barrier to the effective implementation of PtD in the construction industry. In the UK, following her review of construction fatalities, Donaghy (2009) recommended accrediting bodies representing the construction professions establish specific requirements to include OSH in the education of all professionals engaged in the delivery of construction projects. Specific requirements to incorporate construction process knowledge into the engineering and architecture curricula could enhance the effectiveness of PtD policy initiatives.

Quality of risk control as a measure of OSH effectiveness

The research also developed a new method for measuring OSH performance in research. Commonly used measures, e.g. the frequency or rate of occurrence of accidents, are notoriously unreliable measures of safety performance in construction projects. Thus, using accident occurrence as a dependent variable in research is problematic. The use of the HOC provides a more direct and useful measure of the quality of OSH risk mitigation efforts and more directly measures the quality of OSH outcomes. Thus, we propose using the HOC as a valid “leading indicator” of OSH performance in future research.

Conclusions

The failure to address OSH in design is at odds with contemporary thinking in OSH risk management, in which the most effective means of dealing with a hazard is to eliminate it at source. There is compelling evidence to suggest that decisions made during the design stage of a project can have a significant “downstream” impact upon OSH. However, research suggests structural and practical impediments to the effective implementation of PtD in construction projects. The research provides evidence that the integration of process knowledge into product design decisions can significantly improve the quality of OSH risk control in construction. It is recommended that project participants consciously adopt project delivery and management strategies that will support this integration. In addition, the research suggests that the provision, through curriculum change, of construction process knowledge to designers of the constructed product (i.e, engineers and architects) could also help to optimize OSH risk control outcomes.

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