A MULTILEVEL SOCIO-TECHNICAL PERSPECTIVE ON WORK HEALTH AND SAFETY RELATED DESIGN DECISION MAKING

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Research in construction has identified considerable benefits in the integration of construction expertise and knowledge into early project decision making. Improved constructability and health and safety (H&S) have been frequently highlighted among other benefits. Research evidence has suggested that early-stage collaboration and effective interaction within and between design and construction participants are vital to make construction process knowledge accessible to design decision makers. Nevertheless, effective interaction still seems to be a problem in practice and in many cases, the efforts to promote collaborative interactions have failed to cope with the complex nature of the design process. Six case studies were undertaken to explore the way in which the interactions between design and construction decision makers impact on the quality of design decisions and H&S outcomes. The results of one case study are reported in this paper. Social network analysis (SNA) was applied to explore the patterns of interaction between project participants. Unlike the previous applications of SNA in construction, which have largely been cross-sectional and single-level in their focus, a multi-level framework was implemented to recognise the socio-technical complexities and interdependencies in design decision-making. Thus, the design process and its underlying interactions were explored jointly. The study evidence suggested that positive outcomes could be achieved through an alignment between the information interdependencies of the design decisions and the communication patterns that underpin them. The findings of this study can be used to understand, proactively design and maintain interaction networks that support effective decision-making in the context of 'safety in design'.

Keywords: decision-making, health and safety, social network analysis, multi-level

INTRODUCTION

During the past two decades, there has been a growing understanding that the root causes of H&S incidents on construction sites can be linked back to problems inherent in features of work systems conceived in the early life-cycle of construction projects (e.g. planning and design stages). This understanding has led to the recognition of 'safety in design' (SiD) as a proactive H&S risk management approach. SiD aims to anticipate and 'design out' H&S risks at early project stages.

Despite the growing momentum surrounding SiD, research has indicated that, in many cases, designing for H&S has achieved suboptimal results in the construction industry

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(Atkinson and Westall 2010; Gambatese *et al.,* 2005). A number of factors have been proposed contributing to successful implementation of SiD, such as designers' knowledge and attitude towards the concept (Gambatese *et al.,* 2005) and clients' motivation and commitment and involvement of contractors (Goh and Chua 2016). However, a key issue, which remains unresolved, is that the efforts to improve H&S at the design stage have failed to achieve the required level of collaboration and integrated decision-making between design and construction participants.

Previous studies (e.g. Lingard *et al.,* 2014a; Gambatese 2000) have suggested that positive constructability and H&S outcomes are more likely if construction process knowledge is made accessible during design decision-making. Collaborative and effective interaction between participants involved in making design and construction decisions can facilitate knowledge and information sharing between project participants. Thus, participants' knowledge gaps can be addressed and there would be less reliance on inaccurate assumptions. This is particularly important in relation to SiD, which involves knowledge from two main areas, the design of the final product and the design of construction process. However, the organisational and contractual separation of the design and construction functions in projects often impedes free and effective communication between constructors and designers (Lingard *et al.,* 2014a).

Efforts to address this issue have not been completely effective. For example, it has been pointed out that integrated project delivery methods, aimed at addressing the separation between design and construction functions, do not guarantee improved safety outcomes (Atkinson and Westall 2010), and will not generate, as a matter of course, a positive cultural orientation to H&S (Ankrah *et al.,* 2009). In addition, knowledge support tools and processes, which aim to assist designers with H&S related decision-making, mostly take a linear and reactive approach. They normally draw on a limited set of pre-identified design solutions or encourage an add-on review process to enhance H&S after the design has already progressed through its stages and key design decisions are already made. The underlying problem with these efforts is that they mostly fail to acknowledge and cope with the complex and reflexive nature of the design process (Lingard *et al.,* 2014b).

A case study is presented in this paper to explore the way in which project interactions can address the knowledge requirements of design process and facilitate integrated design and construction decision-making. The study explored H&S related design decision-making and its underpinning interactions in a construction project. The aim was to understand the way in which interaction networks support collaborative design decision-making and impact upon construction H&S in the complex context of a construction project. To obtain a realistic view of the design process, a multi-level network analysis approach was combined with in-depth qualitative interviews with project participants. This approach particularly enabled the simultaneous investigation of technical decision interdependencies and the social interactions from which the decisions emerge. Consequently, it was possible to understand which alignments between social and technical aspects of design decision-making can lead to better H&S decision outcomes.

Socio-Technical Complexities Of Design Process

Design is socially and technically complex. Design activity involves a high level of interdependency between technologies, tasks or inputs from participants (Lingard *et al.,* 2012). Design teams are referred to as 'temporary, multidisciplinary and network-based organisations' (den Otter and Emmitt 2008). Design outcomes emerge from a network of inter-related decisions made through repeated interactions between multiple participants. These interactions, in turn, form a complex structure of information exchanges underlying the design decision-making process.

Design is a multi-disciplinary and social process. Design solutions are shaped through the unfolding actions of participants and their interdisciplinary interactions (Çıdık and Boyd 2019). Because of the increased technical sophistication of modern construction methods and products, often, the required design knowledge is possessed by more than one participant (Pektaş *et al.,* 2006). Design knowledge and expertise becomes available during design activities when relevant participants engage in design decision-making and interact with other participants. Tryggestad *et al.* (2010) view construction design work as a collective activity characterized by social negotiations among coalitions of parties who engage in 'trade-offs' to find practicable solutions to emergent problems. Thus, underpinning each technical design decision, there is a network of social interactions between participants who contribute their knowledge and expertise to decision-making. As knowledge requirements of each decision-making scenario are different, the participants and the interaction network between them change at each decision point (Pirzadeh and Lingard 2017). At the same time, design decisions are technically interrelated with some decisions building on, and requiring information from, other decisions. The required information is often transferred between decisions through participants' interactions.

The complex structure of interdependencies between design decisions and the social interactions underpinning them can be conceptualised as a multi-level network. At the macro-level, design decisions and the interdependencies between them form a technical network. At the micro-level, design participants and the information exchanges between them create a social network. The pattern of networks at these two levels are interdependent. On the one hand, design decisions at the macro-level are the outcome of interactions between participants. Each participant, depending on their expertise and decision-making power, exerts a degree of influence on shaping each decision outcome. On the other hand, the motivation for the interactions at micro-level is to address the information requirements of decisions at macro-level. Due to these between-level dependencies, the decision network and the interaction network constantly influence each other and evolve together during the design process. Recognising these multi-level socio-technical interdependencies can facilitate a realistic understanding of the nature of communication and collaboration in relation to SiD decision-making.

A network perspective has been previously applied to study participants interactions during the design process (e.g. Tryggestad *et al.,* 2010; Lingard *et al.,* 2014a). However, this application has predominantly been single level, mainly focusing on patterns of social interactions. For example, a high number of direct communication links between participants in the overall project network, indicated by a high network density, has been interpreted as a sign of better knowledge sharing and higher performance in project teams (see for example Chinowsky *et al.,* 2008). Although useful, this approach does not provide a comprehensive view of design process, as simplification is made by ignoring the decisions for which the interactions take place. Consequently, the important interdependencies between the social aspect of design decision-making (at the micro-level) and the technical aspect (at macro-level) are ignored in the single level approaches. In contrast, the multi-level network approach is powerful for recognizing the socio-technical interdependencies that exist between the macro and micro levels of relationships. In complex socio-technical networks (such as design) analysing relationships at each level in conjunction with relationships at the other level allows more precision and detail, while analysing each level separately, would lead to losing insight about features of the bigger picture (Snijders 2016).

RESEARCH METHODOLOGY

A case study approach was adapted to enable an in-depth investigation (Yin 2009) of socio-technical complexities of design decision-making in a dynamic project context. The design and construction phases of a project were studied to understand the role of interaction patterns in supporting the integration of construction knowledge into design decision making. When selecting the project, it was ensured that (1) the project presented particular H&S challenges, and (2) all key participants involved in making design or construction related decisions were available and willing to be interviewed. Establishing the second criterion improved data reliability and ensured that project participants would be able to directly focus on and recall the decision-making process, the interactions related to it, and the decision outcomes (Lingard *et al.,* 2014a). Data collection was undertaken when the detailed design had mostly completed, and the construction activities were underway. At the commencement of data collection, in-depth interviews were conducted with six key project participants. These participants included the client's representative, client's logistics manager, client's consultant engineer, project manager, structural engineer, and construction manager. The interviews explored key decisions made in relation to design of the structure and their rationale, the process by which the structure was being constructed, the implications of the design decisions on construction process, and the way that construction H&S hazards/risks were controlled. Content analysis of the data revealed the key design decisions with H&S implications, their sequence and the decision circumstances. 19 key design decisions were identified. The data was also triangulated. This was done by comparing the statements of different interviewees and seeking further verification from them where inconsistencies between interviewees' recalls were identified. Thus, the impact of self-reporting bias and recall was minimised.

Subsequently, additional interviews were conducted to collect social network data for each of the key decisions. Using name generators, each of the key participants were asked to identify other participants whom they interacted with during each of the decisions. This approach helped to identify and include other participants in the interaction networks. The participants were then asked to rate the frequency of their interactions with each of the other participants at each decision point. All types of interactions were included. The frequency was captured using a 5-point Likert response format ranging from 1 (occasionally) to 5 (daily). The existence of each communication link was confirmed with both of the interaction participants. Where they rated the frequency differently, the lower value was used. Collecting interaction data at each decision point helped the participants to better focus on the relevant information exchanges associated with design and improved the validity of data. In addition, for each decision, participants were asked to rank other team members in terms of their influence on decision-making. A participant's 'decision-making power' was then calculated by adding up the rates received and was scaled to range from 0-5.

Analysing the multi-level interdependencies

A social network analysis (SNA) technique was applied to visualise and analyse the network patterns at each decision point. In addition, a multi-level network was created to simultaneously capture and analyse the technical interdependencies between design decisions and the social interactions between participants. The macro-level network consisted of the design decisions and the technical interdependencies between them. The micro-level network represented the social interactions that took place between the participants during the design process. The meso-level network indicated the involvement of participants in decisions based on their decision-making power. That is, a tie between a participant and a decision was established where the participant was involved in making the decision and had power to influence the decision outcome. To analyse this network, exponential random graph models (ERGMs) were used.

ERGMs are a class of statistical models for social networks. They facilitate the empirical examination of complex network structures. They are useful for examining multi-level and multi-theoretical hypotheses about network formation (Robins *et al.,* 2007). Using ERGMs, a set of basic network configurations are selected. These configurations are assumed to emerge from local social processes, which may be in action and shape global network patterns (Lusher *et al.,* 2013). Thus, by searching for these local configurations and assessing their prevalence in an observed network, it is possible to test hypotheses about the formation of the network. This is done by comparing observed networks with networks of a similar order which are generated by statistical simulation. If the probability of observing the same network pattern by chance is low, then there is confidence in the hypothesised social processes (Scott 2012). The set of network configurations used in this study and their explanations are provided in Table 1. These configurations represent the possible patterns of socio-technical interdependencies within the network. When illustrating the patterns (in the second column), circles indicate participants and squares signify decisions.

Case study project

The case involved the design and installation of the roof structure for the storage facility of a plant in New Zealand. The project was procured using a design and construct (D&C) approach. At the early stage, the client engaged a consultant to review the design of client's facilities in other locations to capture their best design features. Based on this review, a generic design was developed with a strong focus on operations and end-use features, as well as health regulatory requirements. The generic design specifications were handed over to the constructor. The contractor suggested revisions to the roof design. It was decided to install trussed rafters connecting to the main spine trusses instead of using steel I beams. The trusses weighed less and were quicker and easier to install. All steel was manufactured off-site. Truss sections were transported to the site and bolted together at ground level, then lifted into position. All supporting columns were fitted with a bearing plate allowing trusses to be temporarily supported while connections at each end were bolted. The structure was designed so that erection could be done in self-supporting sections. These decisions greatly reduced the amount of on-site work. The large trusses were manufactured in sections and transported to the site.

RESULTS

Constructor's influence on design decisions

As the interviews revealed, in spite of the client's emphasis on end-use requirements, the constructor was still given authority to make decisions about details of the building design and the construction process, and apply their construction expertise and experience during the structural design process. Decisions about the design and arrangement of roof structural members involved the constructor, constructor's engineer and client's engineer. The constructor was central during the interactions acting as a 'broker', i.e., providing the only point of contact between the other participants. This position, enabled the constructor to involve their experience in design activities and influence decision outcomes to improve constructability and H&S. For example, based on the constructor's experience, a decision was made to use trussed rafters, rather than I beams, resulting in a lighter roof structure which was quicker to erect. Similarly, it was decided to divide each truss span into three smaller sections. This made transportation safer, and reduced workers' exposure to hazards associated with lifting and moving heavy and large objects on-site.

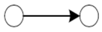
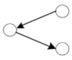
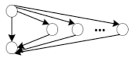
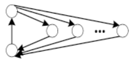
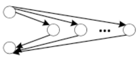
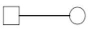
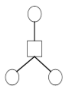
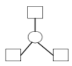
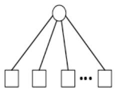
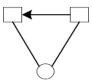
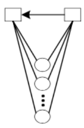
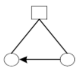
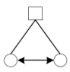
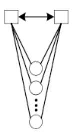
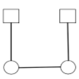
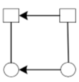
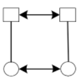
Involvement of subcontractors as a source of construction expertise
The subcontractor (steel erectors) was involved in the interactions in relation to construction process, for example, when it was decided to manufacture the roof trusses off-site. This decision significantly reduced workers' exposure to on-site hazards such as fall from height, electrocution (on-site welding), ergonomic hazards, manual handling, and being struck by objects and equipment during the manufacturing process. In addition, the subcontractor suggested to bolt sections of the main trusses together on the ground and then lift them to their positions. This significantly reduced the amount of time trusses needed to be suspended from the crane, and the time and effort workers needed to spend fitting and connecting sections of trusses at height.

Multilevel analysis of socio-technical interdependencies
Apart from the analysis of interactions at each decision point, a multi-level network analysis was performed. The model comprised both interaction-level (micro-level) effects and cross-level effects. The goodness-of-fit check showed the model was capable of reproducing the properties of the observed network well. The absolute values for the goodness-of-fit ratios were well below suggested thresholds: that is, ratios were less than 0.1 for fitted effects and less than 1.5 for unfitted effects. The results of the network analysis are provided in Table 1. The significant estimates are marked with a * and indicate the associated configurations were observed more than anticipated (if the parameter value had been 0), given the other effects included in the model. The standard errors are provided in brackets under parameter estimates.

The positive and significant parameter estimate for a *multiple connectivity* effect in the model indicates that open two-path configurations were likely. This suggests a tendency for the participants to exchange information through others. Furthermore, non-significant *closure* estimates suggest no tendency for the participants to directly interact. Thus, there was a preference to exchange information through a few central participants in the interaction network. This result agrees with the results from the analysis of interactions at key decision points indicating that the constructor was a central actor and mostly the only point of contact between others.

The positive and significant parameter estimate for *affiliation-based closure* indicates participants' tendency to be directly involved in making sets of interdependent decisions. In addition, the negative and significant estimate for *cross-level alignment entrainment* indicates a low tendency for individuals involved in different, but interdependent, decisions to directly interact. Put together, it can be concluded that the interdependent decisions in this case were more likely to be made through direct involvement of common participants. Thus, the associated information was transferred between dependent decisions through direct involvement of relevant individuals (with power to influence decision outcomes), rather than only through interaction between them. Overall, these significant effects suggest that, where decisions were technically depended on each other, the participants were the primary means of transferring the relevant knowledge and expertise between the decision-making situations.

Table 1: Basic network configurations, their explanations and their estimates in this study

Effects	Pattern	Interpretation in this study	Estimates
Arc		This parameter refers to the baseline tendency for formation of social interaction ties.	-8.3653 (5.389)
Two-path		This refers to the extent to which social actors who send out information also receive information.	-1.0081 (0.699)
Transitive closure		This parameter indicates a tendency for social closure in network.	1.904 (3.209)
Cyclic closure		This parameter refers to the tendency for social interaction to occur in non-hierarchical cycles.	-0.1089 (3.002)
Multiple connectivity		This parameter reflects the extent to which actors interact indirectly through others.	2.6252 (1.189) *
Cross-level edge		This parameter indicates the baseline tendency for actors' involvement in decisions.	-4.628 (2.368)
Cross-level 3-star connectivity		This parameter reflects central decisions in which a high number of actors are involved.	-0.0971 (0.097)
Cross-level 3-star connectivity		A positive value for this parameter indicates there are influential actors involved in multiple decisions.	0.0076 (0.003) *
Cross-level connectivity spread		This parameter indicates influential actors in network who are involved in several decisions.	1.1004 (1.2)
Affiliation-based closure arc		This parameter indicates actors' tendency to be directly involved in interdependent decisions.	1.1498 (0.302) *
Alternative affiliation-based closure arc		This parameter indicates the extent to which dependent decisions involve a number of the same actors who are involved in both decisions.	0.1194 (0.767)
Affiliation-based closure arc		This indicates the tendency of actors involved in the same decision to interact.	-0.8361 (2.124)
Affiliation-based closure reciprocity		This indicates the tendency of actors making the same decision to engage in two-way interaction.	2.7917 (4.306)
Alternative affiliation-based closure reciprocity		This indicates the extent to which interdependent (mutually dependent) decisions involve a number of the same actors.	2.0105 (1.494)
Affiliation and within-level activity		This effect reflects the interaction tendency for actors involved in making unrelated decisions.	-0.006 (0.011)
Cross-level alignment entrainment		Indicates a tendency for actors who are involved in different (but dependent) decisions to interact.	-0.104 (0.047) *
Cross-level alignment reciprocity		Indicates tendency of actors who are involved in different, but mutually interdependent, decisions to engage in two-way interaction.	-0.3489 (0.34)

DISCUSSION

Integrated design and construction decision-making

While the network analysis revealed that the interactions were characterised by the existence of central participants, the interview data indicated that the constructor and design engineer were the highly central participants. The engineer was the main source of design knowledge who developed the detailed design. The constructor, on the other hand, was the main source of construction expertise. Their central role in interactions enabled these participants to input and combine their expertise during the design process. The result of this collaboration was improved constructability and H&S through consideration of construction process during the structure design.

Constructor's central role during communication

The multi-level network analysis helped to further understand the implications of the constructor's central role. The significant and positive effects for *cross-level connectivity* indicated the influential role played by two participants (constructor and constructor's engineer) in shaping design decisions. In addition, the significant and positive multiple connectivity effect reflected the tendency of project participants to exchange information indirectly through influential others. The overall interaction pattern indicated the constructor was the central participant through whom the majority of the information flowed. Hence, the constructor acted as a 'broker' during interactions and both facilitated and controlled the information flow. As the decision-maker about the construction process, this position enabled the constructor to draw on different sources and combine elements of knowledge to create effective solutions. The constructor's central position in the interaction network was coupled with high influence and high decision-making power. As the network analysis and the interviews revealed, the constructor had the highest involvement and influence among all participants. This enabled the constructor to understand the expectations of other parties and access their expertise as required. In addition, the constructor managed to involve their own construction knowledge and experience during the decision-making; that is, act as a source of constructability knowledge and experience where needed.

Involvement of subcontractor in decision-making

The data also revealed a high involvement of the subcontractor (steel erectors) when making key design decisions. The subcontractor was responsible for implementing the construction activities and also possessed the practical expertise about the installation process. The subcontractor's input to the design ensured that the construction process requirements and potential issues were identified and considered during the design of structural components. This finding is in agreement with previous studies which have recognised suppliers and specialist subcontractors for demonstrating innovative and independent decision-making in the design and manufacture of specialized building components (Lingard *et al.,* 2012).

Direct involvement of common participants in making interdependent decisions

The detailed multi-level network analysis indicated a significant and positive *affiliation-based closure* effect, reflecting the match between participants' expertise and decision dependencies and, more importantly, empowering the participants to directly influence decision outcomes where their skills were relevant. For example, the constructor and subcontractor were involved in both the design of trusses and structural connections which also had impact on constructability and H&S. An important finding was that the involvement of the participants was not only through interaction but also by having the power to influence the outcomes of related decisions. This facilitated an efficient and direct transfer of knowledge and expertise between technically dependent decisions.

CONCLUSION

Effective implementation of safety in design benefits from collaboration and effective interaction between project participants. Particularly, the project interaction networks need to support the integration of construction knowledge to the design process. Understanding interdependencies between design decisions and interaction patterns can highlight opportunities for managing communication to produce better decision outcomes. The case study in this paper indicated that aligning the social and technical dependencies of design process can lead to positive constructability and H&S outcomes. Through this alignment, interaction networks would be more likely to address the knowledge requirements of design decision-making. Moreover, the multi-level network analysis indicated that this alignment was improved through two network configurations: 1) the cross-level alignment between interaction ties and decision interdependencies reflecting that the information was transferred between interdependent decisions through participants' communication; and 2) the cross-level (affiliation-based) closure which reflected the participant's high tendency to directly influence the interdependent decisions. While the importance of communication in the context of SiD has been highlighted in previous research, this study provides further evidence indicating that the direct involvement of participants with construction knowledge and their power to actually influence design decisions is a significant factor in achieving positive H&S outcomes. This direct involvement enhances the match between participants' expertise and design decision interdependencies and facilitates the effective mobility and transfer of participants' tacit knowledge between related decisions. In practice, this finding highlights that positive H&S outcomes are more likely when involving construction knowledge in design is coupled with construction participants' power to influence the decisions. For example, in the project presented in this paper, the constructor's ability to influence design decisions, in addition to their frequent communication with other participants, was a key factor for the structural aspects of the building to be designed with consideration of construction requirements. Therefore, to improve the H&S outcomes, project teams need to ensure both the involvement of construction participants in design and their ability to make decisions and influence the decision outcomes.

This study was limited in a number of respects. First, the results from a case study cannot be generalized to other projects. In future, the same approach may be used to conduct further case studies in different project settings. This will enable the comparison of the network features and patterns between cases (in a multiple case study setting) and may lead to stronger conclusions about the features of effective interaction in the context of SiD. Another limitation was the retrospective nature of data collection which involved a reliance on participants' ability to recall design events and communication activities. The impact of this issue was minimised by triangulating the data and conducting multiple interviews with participants from different organisations and roles and confirming the decision-making process and the interactions between them. In future studies, data may be collected in live projects.

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