A Socio-Technical Systems Analysis of OSH Decision-Making in the Early Stages of Construction Projects.

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Abstract

The opportunity to improve the occupational safety and health of construction workers through decisions made upstream of the construction stage is understood to be significant. As a result, policy makers and OSH advisors advocate measures to integrate OSH considerations into the pre-construction activities of planning and design in construction projects. However, OSH guidelines often assume a degree of simplicity in the way that they ascribe responsibility for clients, designers and other stakeholders. This paper explores the ways in which construction projects comprise a complex network of tasks, requiring contributions from many specialists and the involvement of a complicated 'web' of inter-organizational relationships. The paper describes a socio-technical modelling approach that is being used to examine how decisions affecting OSH in the construction stage of projects are made during the planning and design stages. The research will test the oft-cited propositions that the earlier OSH is considered in the life of a project, the greater the opportunity to eliminate/reduce OSH risk at source. The modelling method is illustrated using data collected at a pilot study construction project in Melbourne. Australia.

Keywords: socio-technical systems, occupational safety and health, design, procurement, planning, construction project management

1. Introduction

Poor OSH performance of the construction industry

Internationally the construction industry generally performs poorly in terms of occupational safety and health (OSH). However, the OSH performance of the construction industry varies substantially from country to country. International comparative figures produced by the International Labour Organization suggest that the OSH performance of the US construction industry is notably poorer than that of Australia. For example, the ILO LABORSTA database reports a fatality rate of 4.4 per 100,000 workers for the construction industry in Australia in 2008, compared to a rate of 10.0 for the USA in the same year (See Figure 1). Given these differences, it is useful to undertake cross-national research to understand differences in OSH management practice and performance and to enable international benchmarking of OSH for adoption or adaptation of best practices.

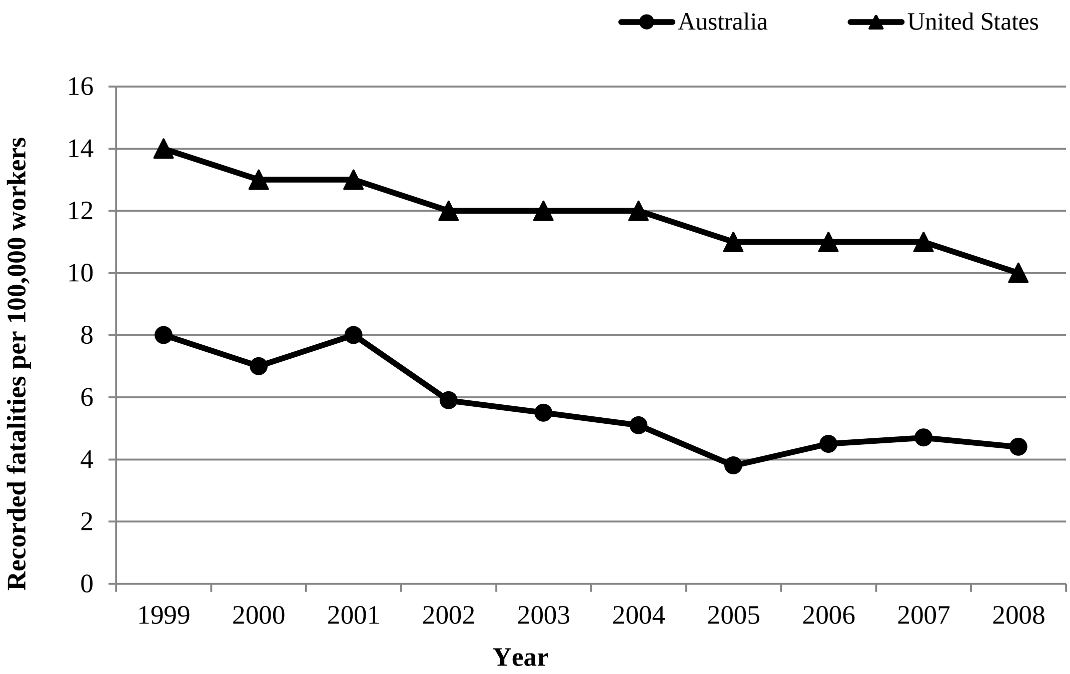


***Figure 1**: Fatality Rates for USA and Australia*

Aim

This paper reports on collaborative research that is being undertaken by researchers in Australia and the USA. The research aims to identify critical socio-technical determinants of project OSH performance in construction projects in both the USA and Australia. Specifically, stage one of the research is mapping, analysing, and modelling the sociotechnical roles, relationships, interactions, and interdependencies occurring during the pre-construction stages of construction projects that subsequently impact on OSH outcomes during the construction stage. The research seeks to empirically test the oft-cited (but as yet untested) propositions that:

(1) The earlier OSH is integrated into project decision making, the greater the realization of hazard elimination/risk reduction at source;
(2) A failure to consider OSH in 'upstream' project decision making will create the conditions in which hazard-producing decisions are more likely to be made; and
(3) 'Higher order' OSH risk controls (i.e., hazard elimination and engineering solutions) are associated with greater concentration of OSH information exchange and stakeholder interaction early in the project process (i.e., in the planning and design stages).

This paper describes the methods being used to analyse construction projects as complex socio-technical systems to gain a better understanding of how decisions made in the early stages of construction projects impact upon project OSH outcomes during the construction stage. Socio-technical systems are those comprised of two or more workers interacting with technology within an organizational and management structure, and internal physical and cultural environment and in the context of an external environment (Kleiner, 2008).

The importance of early consideration of OSH in construction projects

In recent years it has become 'conventional wisdom' to state that the earlier OSH is integrated into construction project decision-making, the more likely it is that OSH problems will be eradicated. Much of this work has focused on the concept of Construction Hazard Prevention through Design (CHPtD) and/or the involvement of construction owners and clients in procuring healthy and safe construction projects. For example, researchers have provided considerable evidence that the design of buildings/structures is a relevant factor in the occurrence of 'downstream' OSH incidents during construction (Behm, 2005, Gibb *et al.* 2004; Gambatese *et al.* 2008). Huang and Hinze (2006a; 2006b) also demonstrate a statistical link between owner/client actions and project OSH performance. Prevention through Design has been deemed worthy of a major goal in the US National Occupational Research Agenda (NORA) strategic plan.

It is often purported that opportunities to reduce OSH risks diminish over time as a construction project progresses through its lifecycle, with risks identified after the detailed design stage of a construction project difficult to eliminate or reduce (Symberski, 1997). Empirical evidence to support Symberski's theoretical 'time-safety' influence curve is almost non-existent. However, some research suggests that project decision-makers' emphasis on safety varies over time and is greatest in the middle of a project, i.e., demonstrating a curvilinear (inverted U-shaped) relationship between emphasis on OSH and time in projects (Humphrey *et al.* 2004).

Policy makers and OSH specialists have advocated interventions aimed at construction professionals in the early stages of projects. However, the extent to which current policy and legislative developments adequately reflect the complexity of construction project decision-making has been questioned and researchers have identified a 'disconnect' between the policy position relating to 'Construction Hazard Prevention through Design' and industry practice (Weinstein *et al.*, 2005).

Construction projects as complex socio-technical systems

Construction project decision-making is characterised by complex inter-organizational relationships, sub-clustering, information dependencies and considerable division of labour (Gray *et al.* 1994, Pietroforte 1995, 1997, Nicolini *et al.* 2001). Significant co-ordination, inter-stakeholder negotiation and compromise is required to complete construction planning and design tasks, often in an environment of uncertainty and characterised by significant external influences (Bibby, 2003). In this context, the influence of a single project stakeholder, i.e, 'the client' or 'the designer', is inherently limited. Consequently, decisions that impact upon OSH cannot easily be traced to a single project participant acting in isolation. As an example, design decisions are not made by a single professional contributor to a project, i.e., the architect or engineer. Rather, design in construction is a political, reflexive process of collective negotiation between multiple contributors and stakeholders (Tryggestad *et al*. 2010) exemplified by numerous interactions. It is therefore difficult to ascribe responsibility to the occupant of a single socio-technical role, i.e., ‘the designer’. Rather, in order to integrate OSH thinking into construction project decision-making, it may be more appropriate to understand construction projects as complex socio-technical systems in which OSH responsibility is a collective rather than individual requirement.

2. Research methods

Case study projects and sampling

A structured case study approach is being used in the research. Project-level data are being collected and analysed to reveal the aetiology of OSH hazard-producing decisions, as well as the decision points and information flows required to achieve the elimination/reduction of construction OSH risks at source. The research involves the collection of data from projects representative of all sectors of the construction industry (e.g., residential, commercial, industrial and heavy engineering), as well as projects procured using different delivery mechanisms (e.g., design-bid-build, design and construct (i.e. build), accelerated (fast-track) and collaborative (alliance)).

Data collection

Data collection at each construction project involves a number of different methods, including: (i) direct observation of project team interactions; (ii) interviews with project team members and other relevant stakeholders; and (iii) inspection of relevant artifacts, such as aspects of the physical worksite and project documentation.

Data analysis

Data are then used to construct a graphic representation of the decision-making of each construction project that impacted upon OSH during the construction stage. This representation maps: (i) decisions taken; (ii) the reasoning for choices made between alternative technological options; and (iii) the social networks of project participants involved in decision-making as the project ‘unfolded’ (See Decision Model below).

The Decision Model components

Project decision-making impacting on OSH is represented in the form of a Decision Model (see Figure 2). The Decision Model uses a socio technical ‘lens’ to reveal construction project decision-making as it impacts upon OSH during the construction stage. The model comprises three components: (i) *layer 1*- an analysis of the rationale of project decisions; (ii) *layer 2* - a process map of key project decisions taken; and (iii) *layer 3* - a social network analysis relating to key project activities. These three components are represented as ‘layers’ in the resulting Decision Model.

3. Pilot study results

Case study project

The Decision Model was piloted and tested at an industrial construction project located in the outer suburbs of Melbourne, Australia. The project involved the reconstruction of a food processing plant that had been damaged by fire. The project was partially subsidised by the State Government of Victoria, which had an interest in maintaining employment created by the food processing plant. The client entered into an accelerated design and construct contract with a builder for the reconstruction of the fire damaged buildings. Data were collected through participatory observations at project meetings, from personal interviews, and from documentary analysis. Data were combined to develop the Decision Model depicted in Figure 2. The model is explained and illustrated below with reference to the design and construction of the structural steel columns at the pilot study food processing plant.

The Decision Rationale

The first layer of the Decision Model represents the rationale for decisions made during the pre-construction stages of the project. This approach draws on a technique used to analyze decisions taken in the design of an artifact, making it particularly helpful for representing decisions made during the planning and design stages of construction projects (Chachere and Haymaker, 2008). The decision rationale ‘layer’ of the model captures choices that are made between available options at key points during project planning and design. The reasons for these choices and ‘trade-offs’ involved form a critical component of the decision rationale, as they highlight constraints and factors that can have important implications for OSH outcomes during the construction stage.

In the case study project, the original fire-damaged production facility was partially intact, yet the design team and constructor expressed a preference for demolishing the entire facility. However, the client’s brief required that only three of the structural steel columns supporting the building be replaced, with the remaining structural components to be retained. This influenced design work, which was further complicated when the client/owner decided to increase the operational capacity of the facility and it was also discovered that many of the columns to be retained were rust-affected. This decision necessitated that existing columns needed to be substantially strengthened to accommodate additional plant/equipment to be installed in the building.

The structural engineer worked in close consultation with the sub-constructor engaged to undertake the column construction work and a number CHPtD solutions were incorporated during the design stage. Prefabrication was not considered to be an option in strengthening the columns because each column varied in its degree of dilapidation and sections of varying length needed to be replaced. The main OSH risk identified in the strengthening work was identified as the risk of falling from height and an elevated mobile work platform was to be used. However, the initial design required temporary props to support columns during the work, preventing workers from gaining access safely. The design was adapted to utilize stiffening plates and remove the need for props, permitting safe access to heights using the elevated mobile work platform. Stiffening plates were to be welded to the columns so that workers would not need to align pre-drilled holes in the columns with holes in the plates at height, further reducing exposure to work at height.

An extract from the Decision Model (Figure 3) shows the design rationale for the structural steel column design, capturing the choices available at key decision points. Decision-makers were faced with a number of constraints and with limited information (for example, not knowing the dilapidated state of the columns when the decision was made to retain the majority of columns from the original structure). Consequently, some key decisions were based upon assumptions made about the structural adequacy of what remained of the original building. Figure 3 shows that the decision pathway changed as information came to light. For example, when the owner/client made the decision to increase the operational capacity of the facility after the commencement of the facility's design, this had an impact upon requirements for the structural steel columns. In the context of these constraints and stakeholder influences, CHPtD solutions that were eventually implemented do not constitute 'ideal' solutions, but represent a 'workable' decision path in the context of the complex project environment. The decisions that impacted CHPtD were influenced by interactions between project stakeholders, available technologies and the project environment, e.g. government funding available to the owner/client to increase the scope of the project. In this context, decisions made reflected 'trade-offs' between technological feasibility, production imperatives and OSH requirements of the operational facility and the construction workforce.

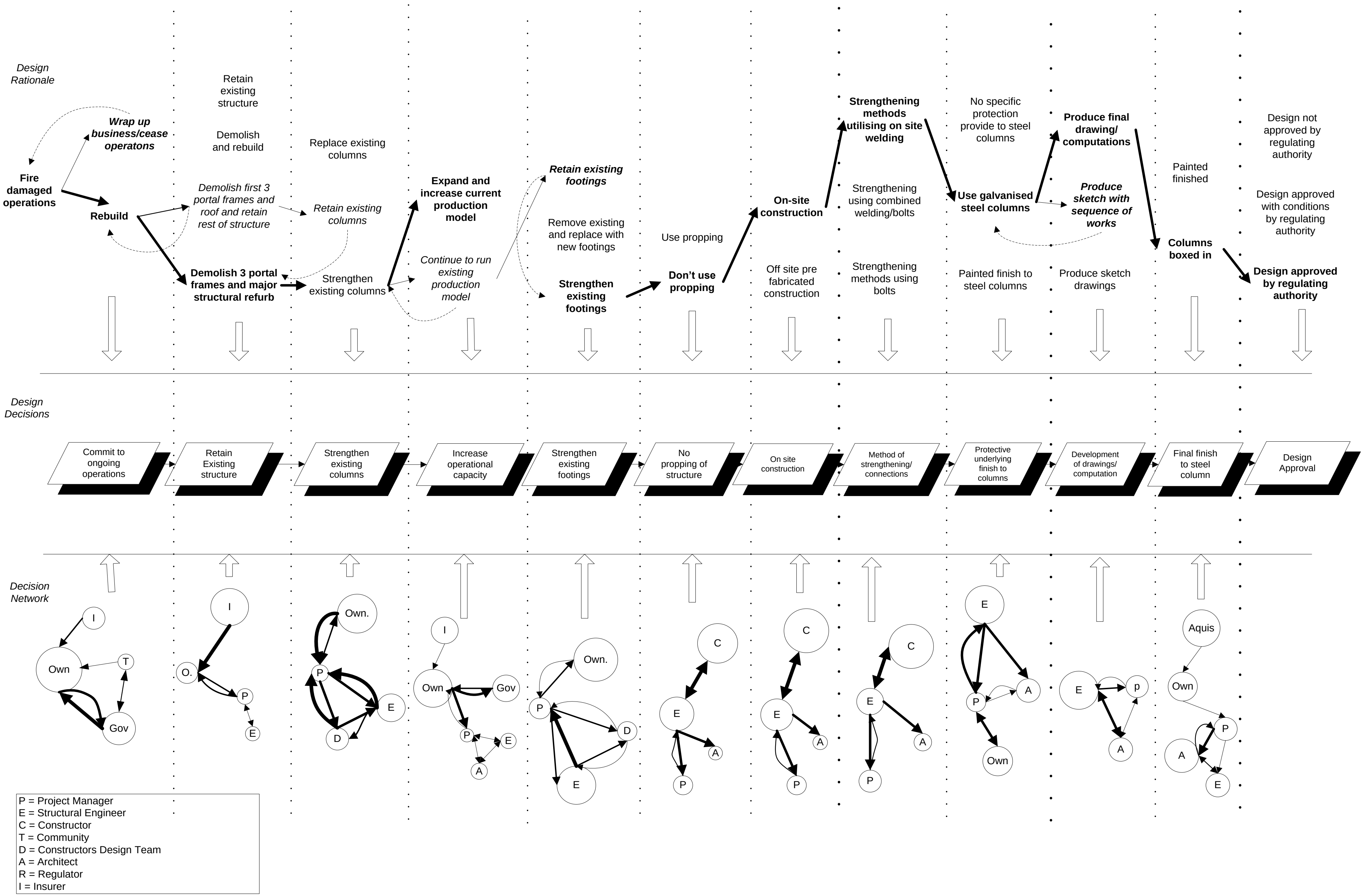


Figure 2: *Pilot Study Decision Model*

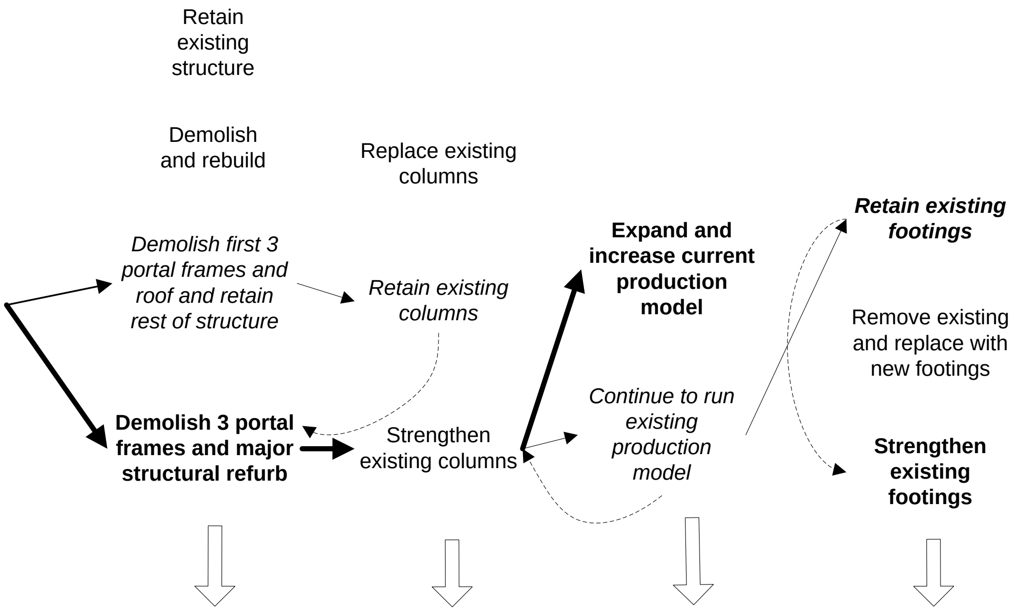
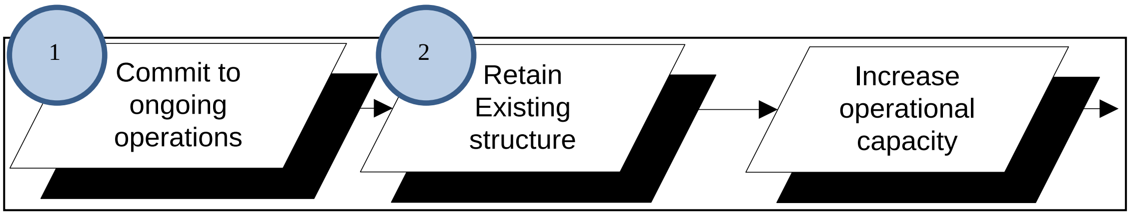


Figure 3*: Extract of Design Rationale from the Decision Model*

The Decision Process

The second layer of the Decision Model borrows from the IDEF0 methodology by focusing on the process functionality (i.e. what is happening) and not on the process organizational structure (who is doing it) (Ang *et al.*,1997). Key decision points within the project are identified. For each decision point, the Decision Model represents: (i) inputs to the decision, e.g., what information was provided to guide the decision-making; (ii) any resources/assistance available to or factors constraining the options available to decision-makers; and (iii) the output, i.e., any product or artifact generated by the decision that was made (See Figure 4).

The extract of the Decision Model reflecting the steel column design is shown in Figure 4. Two key decision points are represented: (i) the decision to rebuild the food processing plant on the basis of a government subsidy awarded to the owner/client; and; (ii) the decision to retain as much of the original fire-damaged facility as possible Each of these decisions was informed by a number of inputs, producing at least one output and was made in the context of a range of constraints and resources, each of which is also captured in the Decision Model. In the case of the pilot project, the column design was primarily driven by time and cost. The client set an ambitious date for the re-opening of the plant, compressing the design and construction work into a ten month period. This set the ‘tone’ for the project with CHPtD decisions contingent on these constraints.



Key Decision Number	Inputs	Constraints	Resources	Outputs
1	▪ Strategic plan for the company ▪ Insurance policy coverage ▪ Employment opportunities in local area	▪ Profit forecasting for operations ▪ cost	▪ Support from Government to fast track permits ▪ Community support to continue operations ▪ influence of permit authority own engineering evaluation	▪ MOU between client and government on funding and permit arrangement ▪ Commitment to continue operations
2	▪ financial support from insurance ▪ operational requirements ▪ structural report on what could be retained ▪ clients identification of what was to remain	▪ cost to rebuild ▪ operational downtime ▪ insurance coverage ▪ time	▪ CAPex ▪ Construction history with constructors and designers ▪ Production outputs	▪ Scope of works

Figure 4*: Extract of Decision Process from the Decision Model*

Social Network Analysis

The third layer of the Decision Model identifies the social entities (individual stakeholders and contributors) involved in a particular cluster of project decisions (for example, decisions made during the design of a particular building element). Social network analytical techniques were used to reveal the relationships and interactions between social entities involved in a decision activity (Scott, 2000; Wasserman and Faust, 1994). Social network analysis is useful because it captures formal as well as informal interactions and is capable of revealing much more information about the social influences on project decision-making than an analysis of formal project documentation can provide (Haythornthwaite 1996). The analysis of social networks enables the most influential stakeholders to be identified within complex project decision networks (Garton *et al*., 1997).

Figure 5 shows example data pertaining to the social networks involved in the design of the structural steel columns at the food processing facility. The social networks illustrate the stakeholders involved in making key decisions (which subsequently impacted on OSH during construction) and reveal the way decisions are made in the context of a construction project. Each network identifies stakeholders involved in a decision, represented as circles (nodes). The arrows between the nodes indicate incoming and outgoing connections, while the thicker lines represent the strength of the relationship and/or frequency of interactions between the stakeholders. The size of the circle represents the power influence in decision making, the bigger the circle, the more decision-making ability that person has.

Figure 5 shows that three key decisions were taken that resulted in retention of most of the original building's columns. While the design team advocated that the remaining structure be demolished and rebuilt to enable the use of off-site prefabrication of new building components, the 'power' stakeholders, the insurer and the owner/client were the most influential in the decision to retain the original structure. Underpinning these decisions were expectations about cost and time associated with demolishing and re-building the whole facility. Ironically, the constructor later commented that the column strengthening "…*took us longer to fix than it would to build a new building*."

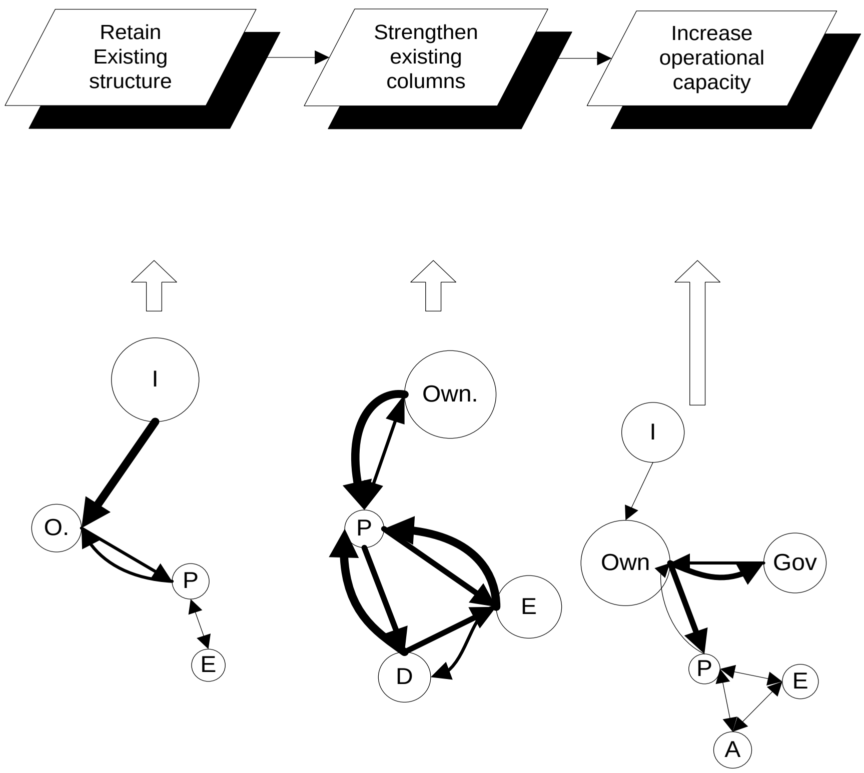


Figure 5*: Extract of Social Network analysis from the Decision Model*

4. Discussion

A socio-technical approach to the integration of OSH 'uptream' of construction

Construction projects comprise a network of tasks, requiring contributions from many specialists (Pryke, 2004). In this paper we investigate the integration of OSH into a construction project decision-making using a socio-technical approach.

Data from the preliminary pilot study project reveal that decisions were influenced by multiple stakeholders with different interests in the project and in the OSH of construction workforce. This is consistent with role analysis in Kleiner's MEAD STS framework (Kleiner, 2008). This was evident in the client's decision to reduce costs by retaining as much of the existing structure as possible, which in turn was influenced by the decision made by the insurance company to only commit to the financial costs of replacing three columns. The initial design appeared to be straightforward, with only three new columns required. However, as the design progressed the scope and complexity increased. Not only did the owner/client's objectives change, but assumptions about the structural integrity of the original building were challenged. Consequently, the steel columns were re-designed in the context of environmental constraints that restricted design choices and introduced specific OSH hazards.

Early integration of OSH into decision-making

While the design team endeavoured to systematically resolve problems as they arose the ability to successfully implement CHPtD proved difficult, with aspects of the project continually changing. The design of the steel columns was an ill-structured problem that evolved as new information came to light. Wholton and Ballard (2002) suggest that this type of problem-solving rarely allows designers to identify all possible solutions, having to settle for choices that satisfy the problem as it is understood at a particular point in time. 'Trade-offs' are inevitable, with decision making becoming as much a social and political process as it is a technical process.

Further, the structural engineering design team were impacted by decisions relating to the selection and positioning of new plant and equipment to be installed in the facility. It is not uncommon for the design of a structure to be decomposed into smaller tasks, assigned to different specialist design 'teams'. The elements in these tasks are designed individually and then combined into larger solutions (Lu, 2000). However, decisions made in one design task that resolve identified OSH hazards create constraints relating to other design tasks. Further, the 'knock-on' effects may not be realised until construction when the constructor is expected to transform the various parts of the design into physical reality.

OSH risk controls

The way in which OSH was dealt with in the design of the structural steel columns at the pilot study project revealed that OSH was integrated into the engineering design of the columns. This was facilitated by close communication and cooperation between the structural engineer, the principal contractor and the subcontractor engaged to undertake the column strengthening work. For example, the decision to bolt sections of steel plating to strengthen the columns constituted an innovative engineering design solution. In this way CHPtD was integrated into the design, albeit in relation to designing the process of construction rather than in the design of the columns themselves.

The modelling of decision-making across multiple projects in different industry sectors will enable an analysis of the extent to which early involvement of construction knowledge and/or frequent and strong relationships between multiple project stakeholders early in the project enhances the implementation of technological solutions to OSH risk.

It was not possible to state, with any certainty, the degree to which the CHPtD choices made in the design of the steel columns at the pilot study project 'succeeded' or 'failed'. However, involving the contractor in the design, upstream of construction was perceived to be particularly beneficial to the workers OSH , "*on other jobs they just give you stuff and you end up having to deal with it." (interviewee).*

Safety critical roles - Stakeholder Influence

Identification of the stakeholders involved in the design of the steel columns showed that those involved in the decision making extended beyond the 'traditional designer' of architects and engineers, to include the client and the insurer. What was also evident was that the decision making process was not a consistent social network over the course of the column design, with the participation of different stakeholders at different stages of the design. As a result the source of the decision power also changed, depending on the stage of the key decision. This in turn impacted on the criteria used to determine the suitability of a key design. Friedman and Miles (2002) found that the interests of stakeholders can vary over the life of a project, as can alliances between stakeholders. External reasons have also been cited as causing changes in the objectives of stakeholders, such as a modification of community preferences which in turn influences political, environmental and community stakeholders, government policy, and the position of other stakeholders (Frooman and Murrell, 2005).

Understanding the roles and social relationships within construction projects is vital for appreciating how OSH can be integrated into project decision making. Our results indicate that simple attributions of OSH responsibility to persons who occupy a particular professional role, e.g. a 'designer' does not reflect the division of intellectual labour, power and influence in project teams.

5. Conclusion

The integration of OSH into pre-construction decision-making is strongly advocated and there is compelling evidence that the activities of clients/owners and design professionals have an important impact on the OSH of construction workers. However, to understand the how best to actively integrate OSH into pre-construction project decision-making, it is important to understand not only the determinants of technical decisions that are made, but also the role, power, interactions and influence of multiple stakeholders whose actions and interests play a critical part in shaping the many decisions that impact upon OSH in the project.

This paper introduces a three level Decision Model that is being deployed in an attempt to gain a better understanding of how social and technical subsystems interact to shape construction OSH outcomes in case study projects in both the USA and Australia. Ultimately, this will assist with "joint optimization", the STS concept of jointly designing the social and technical systems. The pilot study suggests that project decision-making that impacts upon construction OSH is influenced by multiple stakeholders and their interface with technologies. In this context, the prescriptive application of safe technologies can only solve part of the construction OSH problem as genuine integration of OSH into upstream decision-making will require collective action on the part of multiple stakeholders, whose interests may not naturally align with construction workers' OSH.

Future Research

Data will be collected at approximately 32 case study projects representing four industry sectors and four different procurement approaches in both Australia and the USA. The research will enable an analysis of the conditions in which OSH outcomes are enhanced by effective upstream integration of OSH considerations. Opportunities to transfer good practice between countries and/or between industry sectors will be identified. The research will also test the proposition that collaborative project procurement lends itself to more effective integration of OSH into early project decision-making than traditional design-bid-build approaches. Finally, the socio-technical systems analysis will enable safety critical roles to be identified and provide guidance for a realistic basis for sharing OSH responsibility within project teams.

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