Centre for Construction Work Health and Safety Research

Research Summary Report

Safety in Design

The analysis of socio-technical influences on WHS risk

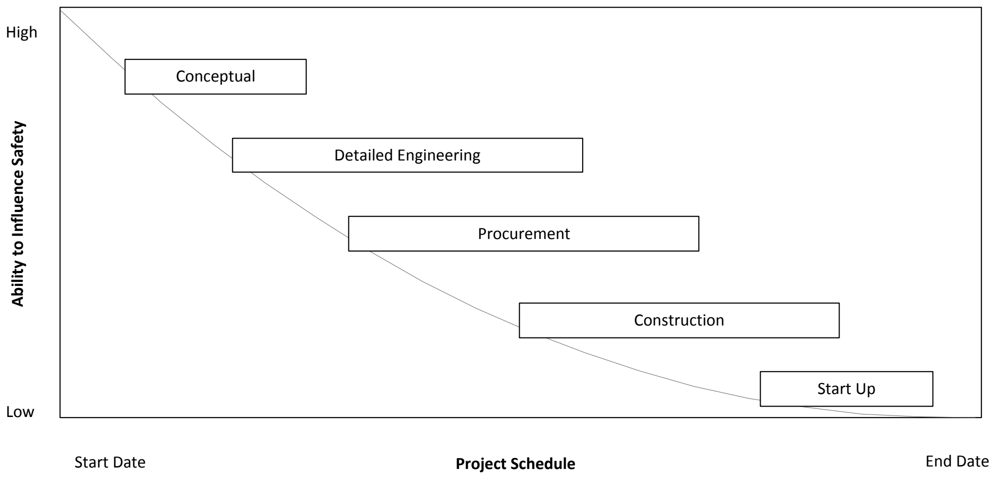
The research project

The practice of anticipating and 'designing out' work health and safety (WHS) hazards (referred to as safety in design) has become a key feature of government policy in many countries, including Australia. Safety in design is a key action area in the Australian Work Health and Safety Strategy 2012-2022 and legislation requiring designers of buildings and structures to consider WHS in their decision-making has been implemented. While not a statutory requirement in the United States, 'Prevention through Design' is a strategic goal cited in the National Construction Agenda for Occupational Safety and Health in the US construction sector.

In the construction industry it is often argued that opportunities to reduce WHS risk are highest at the beginning of a project and dramatically reduce as the project progresses. By the construction stage it is believed that the opportunities to reduce WHS risk are greatly reduced.

This is depicted in Figure 1 below.

Figure 1: The time/safety influence curve (adapted from Szymberski, 1997).



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Challenges associated with implementing safety in design

Barriers to the implementation of safety in design in the construction industry have been identified. These include:

- the organisational and contractual separation of the design and construction functions which is an impediment to free flowing communication between constructors and designers,
- designers' limited knowledge of construction methods and site WHS issues,
- the attribution of WHS responsibility to "the designer" presents difficulties when design work is undertaken in complex inter-organisational network arrangements, and
- linear approaches to WHS risk management assume a level of design stability that does not reflect the complex, dynamic and iterative nature of design work in the construction industry.

Research project aims

Research undertaken within the Centre for Construction Work Health and Safety sought to investigate ways in which better WHS risk reduction outcomes could be achieved in the adoption of safety in design in the construction industry. In-depth analysis of case study projects in Australia and the USA enabled the identification of conditions that produced higher quality WHS risk control outcomes.

The research was undertaken in collaboration with researchers from the Centre for Innovation in Construction Safety and Health at Virginia Tech. (USA) and formed part of a five year international benchmarking study of construction WHS.

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 WHS risk control outcomes, and
- the extent to which early consideration of WHS risk in the project life cycle produces better WHS risk control outcomes.

The efficacy of WHS risk control

In this research, the quality of WHS risk mitigation was measured as a leading indicator, with reference to the 'hierarchy of control.' There is a growing recognition that the evaluation of WHS practices should assess the quality and effectiveness of risk control outcomes. The hierarchy of control (HOC) classifies ways of dealing with health and safety hazards according to the level of effectiveness of the control. At the top of the HOC is the elimination of a hazard altogether. This is the most effective form of control because a hazard is physically removed from the work environment. The second level of control is substitution. This involves replacing something that produces a hazard with something less hazardous. Further down the hierarchy, again, are engineering controls that isolate people from hazards. All of these top three layers of control may be classed as technological control because they change the physical work environment. In contrast, the bottom two layers in the HOC represent behavioural controls in that they seek to change the way people work. Administrative controls, such as developing safe work procedures or implementing a job rotation scheme to limit exposure. At the bottom of the hierarchy, the lowest level of control is personal protective equipment. Personal protective equipment is regarded as the control of last resort because it is the least reliable of the control measures.

It is sometimes argued that safety in design has the ability to produce higher order (i.e. technological) controls for health and safety risk. However, little empirical evidence has been presented to support this claim. This research sought to address this gap.

Considering WHS in early project decision-making

Many frequently cited safety in design "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. Consequently, many safety in design practices in the construction industry produce relatively modest reductions in the level of WHS risk experienced by workers.

One reason for this might be because, in practice, safety decisions are left to the parties engaged in the construction stage. Small modifications to the design of the construction process might be possible, but fundamental changes cannot be made at this point. Leaving decisions about WHS to the construction stage of a project will produce sub-optimal results because key decisions and the safety consequences that flow from them are already fixed. Arguably WHS solutions identified at this stage are likely to focus on trying to change workers' behaviour, rather than trying to eliminate hazards from the physical workplace or construction process.

During the research, data were collected from a total of 23 construction projects –10 in Australia and New Zealand, and 13 in the United States. In each project, specific elements or components of the building (or other facility) were selected. The total number of elements in the analysis was 43. Elements included roof structures, sewerage systems, retaining walls, a pedestrian bridge, and foundation systems. Project stakeholders involved in the planning, design and construction of the buildings (or other facilities) were interviewed. Interviews explored design decisions made for each element, the construction process for the element, and the way WHS hazards were controlled during construction. Interviews also explored the timing and sequence of key decisions about each element and the influences that were at play as design decisions were made. A total of 288 interviews were conducted (185 in Australia and New Zealand, and 103 in the USA). The average number of interviews per feature of work was 6.7. For each building (or facility) element, a score was generated that reflected the quality of WHS risk controls implemented during construction. This score was based on the HOC.

Each HOC level was given a rating ranging from 1 (personal protective equipment) to 5 (elimination). The risk controls implemented for hazards presented by each element were assigned a score on this 5 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.

The point in time was recorded at which a risk control solution was identified, that is, whether this occurred in the project's pre-construction or construction stage. For each building/facility element, the number of WHS solutions selected during the pre-construction stage was expressed as a percentage of the total number of safety solutions for that element – the percentage reflected the extent to which WHS was considered early in the project lifecycle.

Table 1 shows the mean HOC scores for cases by industry sector, project type and country. Australian cases in the analysis had significantly higher average HOC scores than the US cases.

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

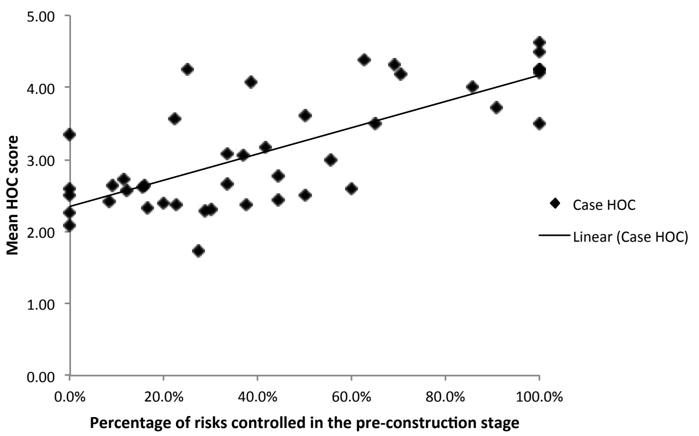
Case descriptor	Mean HOC score	Standard deviation
Country		
United States	2.48	.311
Australia	3.69	.671
Delivery method		
Collaborative	3.36	.632
Design and Build	3.38	.233
Accelerated	2.98	.820
Design-bid-build	2.71	.602
Sector		
Heavy engineering	3.33	.844
Residential	3.02	.777
Commercial	2.72	.649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

Figure 2 shows the relationship between:

- the extent to which health and safety risk controls were considered and decided upon before construction commenced (that is, in the planning or design stages of the project), and
- the quality of risk control outcomes (that is, the average HOC score).

A positive relationship was found, meaning that the greater the proportion of WHS risk controls that were identified and chosen before construction commenced, the better the quality of WHS risk control. This relationship was also statistically significant.

Figure 2: Linear relationship between the pre-construction WHS intervention and the mean HOC score



This research provides some evidence for the link between:

- early consideration of WHS (in pre-construction stages of the project lifecycle), and
- implementing higher order controls for WHS risk.

The research confirms the benefits of considering construction workers' WHS when making decisions about the design of buildings (and other facilities).

The effect of early constructor involvement

There are considerable benefits to involving constructors early in design decision making because of their centrality to the web of stakeholders who participate in construction activity. These benefits arise because:

- constructors have specialised training, knowledge and experience in applying construction materials and methods,
- they are in the best position to provide advice about WHS hazards/risks and ways to mitigate them in construction activities, and
- they are responsible for a project's construction operations – they have a strong motivation and interest in ensuring work is performed with minimal risk to health and safety.

The Australian-US safety benchmarking study also investigated whether involving constructors in decision making during the project design stage produced better WHS risk control outcomes. A technique known as social network analysis was used. Social network analysis is an analytical tool that studies the exchange of information between people who make up a network. Social network analysis was used to map the social relations between project participants in each of the Australian case studies. The constructors' position of 'centrality' in the social networks was quantified. 'Centrality' refers to the extent to which a person is connected to other people – that is, the ratio of the number of relationships the person has relative to the maximum possible number of relationships they could have. Degree centrality is sometimes used as an indicator of the power or influence a person has within a network. In the case study projects, the constructors' centrality was measured during the design stage of the project. The relationships between members in a social network can be visually mapped to produce a sociogram. The resulting diagrams provide a graphic representation of the position and importance of participants within a network.

The cases were split into those with:

- high HOC outcomes (in which predominantly technological risk controls were implemented), and
- low HOC outcomes (in which predominantly behavioural controls were implemented).

The design stage centrality scores for the constructor were compared between high HOC cases and low HOC cases. There was a statistically significant difference:

- in the high HOC cases, the constructors' design stage centrality was 14.2, and
- in the low HOC cases, the constructors' design stage centrality was only 5.4.

These results suggest that the effective transfer of construction knowledge to design decision makers enables improved WHS risk control outcomes.

Case Study: 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 WHS 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 'I-beams' as rafters. The fabrication of rafter trusses was slightly more expensive, but these trusses weighed less than 'I-beams' and could be manufactured offsite. 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.

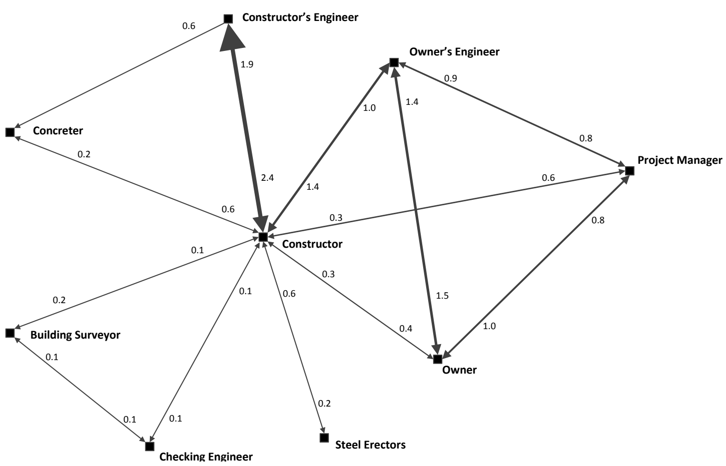
All supporting columns were fitted bolting with a bearing plate allowing trusses to be supported temporarily while connections at each end. This reduced the need for propping and manual handling associated with installing and dismantling props. It also freed the area around the columns and under the trusses of any obstacles or trip hazards that props may have caused. 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 WHS 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. This method enabled the constructor to ensure that crane lifts were within safe reach tolerances, without having to extend the crane's 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 to review the design and erection/installation sequences. The resulting safety in design solutions resulted in an HOC score of 4.2.

Figure 3 is a sociogram that shows the pre-construction social network for this project. The data revealed relatively high 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 subcontractors (steel erectors and concreters). These suppliers and subcontractors possess practical knowledge about constructability 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 WHS risk control.

Figure 3: Sociogram for the steel column and roof design at a food processing and storage facility



The sociogram shows three groups:

1. on the right hand side of the network are key demand-side stakeholders, including the owner, owners' engineer and project manager,
2. on the left hand side of the network are key supply-side stakeholders, including the concreters and steel erectors, and
3. also on the left hand side of the network are stakeholders who supply design-related information and services to the network – 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:

— identified constructability issues before construction commenced, and

— drove the redesign of various components which still met the owner's operational requirements for the facility, and which complied with regulatory requirements.

Conclusions and recommendations

The organisational and contractual separation of the design and construction functions reduces the possibility of free flowing communication between constructors and designers. This is a problem for the implementation of safety in design because communication is critical to the effective performance of construction project teams.

The research provides preliminary support for the time/safety influence curve by demonstrating that WHS risk control outcomes are significantly better when WHS is considered before construction work commences.

The research also demonstrates that transfer of construction knowledge to decision-makers in the pre-construction (planning and design) stages of a construction project life cycle, is associated with the adoption of more effective means of controlling WHS risk.

The research provides evidence to suggest that safety in design is most effectively implemented in construction projects when:

— WHS is considered early in the project life cycle, and

— detailed knowledge of construction processes is available to and used by design decision-makers.

It is recommended that:

1 WHS risks be considered and addressed at the earliest opportunity in a construction project life cycle. Pre-project decisions should be informed by the "downstream" impact that these decisions will have on the WHS of construction workers, and

2 specialist and relevant knowledge of construction processes is accessed and used to inform design decisions.

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