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Prevention through design: trade-offs in reducing occupational health and safety risk for the construction and operation of a facility

Research Paper

Abstract

Purpose – The research explores the interaction between design decisions that reduce occupational health and safety (OHS) risk in the operation stage of a facility's life cycle and the OHS experiences of workers in the construction stage.

Design/methodology/approach – Data was collected from three construction projects in Australia. Design decisions were examined to understand the reasons they were made and the impact that they had on OHS in the construction and operation stages.

Findings – The case examples reveal that design decisions made to reduce OHS risk during the operation of a facility can introduce new hazards in the construction stage. These decisions are often influenced by stakeholders external to the project itself.

Research limitations/implications – The results provide preliminary evidence of challenges inherent in designing for OHS across the lifecycle of a facility. Further research is needed to identify and evaluate methods by which risk reduction across all stages of a facility's life cycle can be optimised.

Practical implications – The research highlights the need to manage tensions between designing for safe construction and operation of a facility.

Originality/value – Previous research assumes design decisions that reduce OHS risk in one stage of a facility's life cycle automatically translate to a net risk reduction across the life cycle. The research highlights the need to consider the implications of PtD decision-making focused on one stage of the facility's life cycle for OHS outcomes in other stages.

Keywords: Prevention through design, Occupational health and safety, construction, operational safety, industry policy.

Introduction

Prevention through Design (PtD)

James Reason (1997) suggests that organizational accidents occur as a result of the complex interaction between organizational and workplace factors and individuals' actions. In some situations, a system's defences fail as a result of latent or underlying conditions which can originate "upstream" of the work itself. In construction, the design of a building or structure has been identified as a causal factor in workplace accidents. In Australia, the National Occupational Health and Safety Commission reported that 37% of 210 workplace fatalities definitely or probably involved design-related issues (NOHSC, 2004). In the USA, Manuele (2008) noted workplace or work process design to be a causal factor in 35% of industrial accidents. Based on the mounting evidence that design contributes to accidents, 'Prevention through Design' (PtD) has emerged as a key occupational health and safety (OHS) policy issue in many countries (Creaser, 2008). For example, Australia's National Occupational Health and Safety (OHS) Strategy 2002 – 2012 identified "eliminating hazards at the design stage" as one of five priority areas (NOHSC 2002).

Definitions of PtD reflect the need for OHS hazards presented by a design to be identified and eliminated or, if elimination is not practicable, the risk presented by that hazard is to be reduced to as low as reasonably practicable (a requirement sometimes referred to as the ALARP principle). This creates the need for decision-makers to apply a risk management methodology and also presents challenges for decision-makers. These will be described in a subsequent section.

Most definitions of PtD imply designers should address hazards across the entire life cycle of a product. For example, the US National Institute for Occupational Safety and Health (NIOSH) defines PtD as "addressing occupational safety and health needs in the design process to prevent or minimize the work-related hazards and risks associated with the *construction, manufacture, use, maintenance, and disposal* of facilities, materials, and equipment" (italics added). Schulte *et al.* (2008, p.115) define PtD as "the practice of anticipating and 'designing out' potential occupational safety and health hazards and risks associated with new processes, structures, equipment, or tools, and organizing work, such that it takes into consideration the *construction, maintenance, decommissioning, and disposal/recycling* of waste material, and recognizing the business and social benefits of doing so" (italics added).

PtD in construction

Research has shown a link between design and safety in the construction industry. An analysis of 100 non-fatal incidents in the United Kingdom revealed that, in approximately half of the cases, an alteration to the permanent works design would have reduced the risk of the accident (HSE 2003; Gibb *et al.* 2004). In the USA, Behm (2005) undertook a review of 224 construction fatalities, finding that, in 94 cases (42%) the design was linked to the incident. Gambatese *et al.* (2008) validated Behm's findings using an expert panel to review a subset of the 224 fatalities originally analysed. In Australia, Driscoll *et al.* (2005) report 44% of construction fatalities to be related to design, although they acknowledge that 'informational difficulties' made it difficult to ascertain whether these

fatalities could be attributed to: (i) the permanent design of the building/structure, (ii) the design of plant/equipment, or (iii) the design of the process of construction, including temporary works.

Narrow interpretations of PtD in construction

Despite 'cradle-to-grave' definitions of PtD, research in the construction industry often targets a single stage in the life cycle of a building/structure for PtD intervention. For example, Cooke *et al.* (2008) developed a knowledge-based decision support tool to provide designers with 'expert' OHS knowledge. Although only a prototype, this tool was limited to design features that impacted upon OHS risks during the maintenance of a building. Some PtD examples have the potential to reduce OHS risk in both the operation of a facility and during construction. For example, the UK's Health and Safety Executive has produced guidance material in the form of 'Red, Amber and Green' lists, which identify a number of design solutions that effectively reduce OHS risk in both the construction and operation/maintenance stages (HSE, 2012).

PtD policy and legislation

Prevailing PtD policy and legislation can focus on one stage in the life cycle of a facility, at the expense of other stages. For example, in the Australian State of Victoria, Section 28 of the *Occupational Health and Safety Act* (2004) requires designers of buildings or structures to ensure that buildings or structures are designed to be safe and without risks to the health of persons using them as a workplace. WorkSafe Victoria (the OHS regulator) has published guidance stating that design of the construction and demolition phases of a building or structure's life cycle are outside the scope of Section 28 (WorkSafe Victoria, 2005). In the United Kingdom, the *Construction Design and Management Regulations* (2007) establishes broader responsibilities, requiring designers to avoid foreseeable risks to any person: (i) carrying out construction work; (ii) liable to be affected by such construction work; (iii) cleaning any window or any transparent or translucent wall, ceiling or roof in or on a structure; (iv) maintaining the permanent fixtures and fittings of a structure; or (v) using a structure designed as a workplace.

The possibility of trade-offs in risk reduction

PtD guidance often implicitly assumes design measures that reduce OHS risk in one stage of a product's life cycle are beneficial (or at least have no negative impacts) on OHS risk in other life cycle stages. This may be problematic in the construction industry. Wright *et al.* (2003) foreshadow the possibility of conflict between designing for OHS in the construction and operation stages of a facility when discussing the implications of using built up, compared to composite panel, roofing systems. Although composite roofing systems reduce the need for work at height during installation, they present an increased risk of falling during roof maintenance (Wright *et al.* 2003).

Stakeholder theory

A common problem inherent in PtD policy is the attribution of responsibility to the occupant of an abstract socio-technical role, i.e. "the designer." Design work in the construction industry is an emergent, iterative process in which multiple stakeholders interact to shape decisions (Tryggestad *et al.*, 2010; Ewenstein and Whyte, 2007).

Research reveals how stakeholders' concerns and priorities change over the life of a construction project (Olander 2007). Thomson (2011) presents an industry case study revealing that stakeholders' understanding of what they want from a construction project develops through their reflection on emerging design solutions. Thus, rather than viewing design as a linear process characterised by stability and predictability, Thomson argues design should be regarded as an iterative and reflective process in which stakeholders engage in continuous negotiation and learning.

Risk management challenges

PtD requires the adoption of a risk management method, in which: (i) the impact of potential risky events is considered; (ii) strategies for controlling risks are identified; and (iii) these strategies inform managerial decision-making (Ridley and Channing 1999, p. 6). However, determining the magnitude of a risk is not straightforward. Even technical experts have been shown to have widely varying risk perceptions (Slovic et al. 1980). Risk judgements are shaped by the way that a risk problem is framed (Pigeon et al. 1993). Research also reveals how social groups perceive and experience risk differently (see, for example, Vlek and Stallen, 1981). Thus, a level of risk that is acceptable to one group, may not be to another. Pidgeon (1996) describes 'plural rationalities' as competing and equally legitimate viewpoints concerning risk. Construction is a complex industry in which those who make professional decisions, including those concerning the design of a facility, belong to a different social group to those whose health and safety could be affected by those decisions. Previous research has revealed significant social differences in judgements about OHS risk in the construction industry (Holmes and Gifford, 1997). In applying risk management to PtD, decision makers are expected to consider the potential for a design to impact on the OHS of one or more other social groups, and make decisions that will reduce these risks to being 'as low as is reasonably practicable' (ALARP). The application of risk management presents a significant challenge as decision-makers must judge 'how safe is safe enough?' and decisions inevitably involve trading off the risks and benefits of a hazard to all social groups (Starr, 1969). In this context it seems useful to explore whether the implementation of PtD involves making trade-offs and, if so, how these trade-offs impact upon the OHS of different social groups impacted by construction projects.

Aim

Little research has investigated risk reduction trade-offs in implementing PtD in the construction industry. The aim of this research was to investigate PtD decisions and outcomes in the construction industry, to gain a better understanding of the relationship between designing for OHS in the construction and operation stages of a facility. The research is being conducted in both the United States and Australia as part of an international collaborative benchmarking study. This paper reports some of the Australian findings. Specific research objectives were:

- (1) to describe and analyse how OHS in the construction and operation stages of a facility is influenced by decisions about the permanent design of a facility;
- (2) to investigate the interaction between designing for OHS in the construction stage and the operation/maintenance stage of a facility; and
- (3) to consider the implications of the interaction between designing for OHS in construction and operation for the management of PtD in the construction industry.

Research Methods

The research adopted a case study approach, favoured for the rich causal data that it produces (Orum *et al*, 1991; Eisenhardt, 1989; Fellows and Liu, 1997; Yin, 1994). Data were collected using a number of different methods including: (i) direct observation of project team interactions, (ii) interviews with project participants and stakeholders, and (iii) inspection of artefacts, such as aspects of the physical worksite and project documentation.

Larsson (2007) reports that, when asked to describe their behaviour, people tend to give an account closer to the ideal than the manifest. For this reason direct observation of project team meetings was essential to gaining an accurate understanding of the reasoning and motivation behind design decisions that were made in each case. The researcher attended design team meetings at three different case study construction projects. Projects were selected to represent a variety of project types and included a commercial/industrial building project, a water infrastructure project and a rail infrastructure project. Projects were selected on the basis that all key project participants (including, as a minimum, the design consultants, the construction contractor and the client) were willing to participate in the research.

Direct observation of project participants was followed by a series of interviews concerning the design of selected elements of the facilities. The researcher purposefully identified specific design elements for analysis on the basis that these elements illustrated the interaction between OHS in the construction and operation stages of the facility. For each element, relevant stakeholders were identified and interviewed. The interviews explored project stakeholders' reasoning relevant to design decisions as these decisions 'unfolded' in the project context.

The legislative context

In Australia, OHS is regulated at the state/territory level. Historically, significant differences have existed in statutory OHS requirements across Australia. A recent initiative to harmonise OHS legislation across Australia hinged upon the enactment by all states and territories of a *Model Work Health and Safety Act*. However, this harmonisation initiative has foundered, with a number of states failing to enact new legislation in the requisite timeframe (by January 2012), and jurisdictional differences in OHS legislation even in the states in which the Model Act has been adopted. Two of the case study projects (one and two) were situated in Victoria. At the time of the data collection there was no statutory requirement under the Victorian OHS legislation for designers to eliminate or reduce OHS risk to construction personnel (See WorkSafe Victoria, 2005). The third case study project was situated in the Australian Capital Territory (ACT). In the ACT, Section 22 of the *Work Health and Safety Act* (2011) requires designers of structures to be used as a workplace to design the structure to be without health and safety risks to people who use the structure for its intended purpose, as well as people who construct the structure or who are engaged any reasonably foreseeable activity involving the manufacture, assembly, use, demolition or disposal of the structure. Thus, the legislative responsibilities for PtD are considerably broader in the ACT than in Victoria.

Results

Case information

Information about the case study projects is provided in Table 1. Total project value ranged from AU\$100 million (the food processing facility) to AU\$3 million (the installation of the centrifuge in a sewerage treatment plant). Two projects were brown field sites involving the reconstruction or upgrade of an existing facility. One project (the suburban train station) was a green field project. Projects ranged from 6 months (the installation plant at a sewerage treatment plant) to 18 months (the suburban train station) in duration. In each of the cases changes were made to the design in order to improve the OHS of end users. In two of these cases (the food processing facility and the sewerage treatment project), the design changes were made after construction had commenced. The design change was made at the full conceptual design phase of the suburban train station project.

Table 1: Case study overview

Case No.	Total cost of project	Duration of project	Development type	Phase at which a design change was introduced	Design issue	Design change details
1.	≈AU\$100 million	10 months	Brown field (fire damaged)	Phase 8 – Construction	Fire rating of a large isolated building	Installation of a fire-rated wall with fire rated penetrations and a sprinkler system.
2.	≈AU\$86 million	18 months	Green field (new train station)	Phase 5 – Full conceptual design	Access to a new train platform	Installation of a new pedestrian ramp, in addition to stair and lift access.
3.	≈AU\$3 million	6 months	Brown field (facility upgrade)	Phase 8 - Construction	Installation of a new working platform	New cantilever platform required to be installed, providing full perimeter access to a new, larger replacement centrifuge.

Note: The Generic Design and Construction Process Protocol (Kagioglou *et al.* 1998) was also used to identify the project phase in which a change was made to the permanent design.

Case 1 – Fire rating a food processing facility

The first case arose during the design and reconstruction of a food processing facility situated in the outer suburbs of Melbourne. The plant had been partially destroyed by a fire in January 2010, resulting in closure and the loss of 1,700 jobs in the local area. To prevent the loss of employment in the area, the State Government of Victoria offered substantial monetary assistance to the client to support re-construction and fast-tracked the planning process to facilitate this. As a consequence of this support, the client decided

to re-build the plant and appointed a contractor under a 'design and build' contract to undertake the project.

The client originally requested that a sprinkler system not be installed in the food processing building. However, after construction work had commenced, a registered building surveyor advised that, if a sprinkler system was not installed, to satisfy the Building Code of Australia (BCA), a fire-rated wall would have to be incorporated into the building design to reduce the size of the building compartments.

The decision to include a fire wall was consequently made once the primary structure was constructed. As the 'design and build' contractor's project manager commented: *"We were literally putting up a building when we found that our areas were over what we thought they were. Whereas normally you would be in a conceptual design you would see it and stop and evaluate it, whereas having been committed to a building out there, we had to make the decision [to include a fire wall]."*

The original plan was to erect the fire wall using a 'tilt-up' panel method of construction. However, penetrations would need to be made in the wall to accommodate plant and services and, at that stage, the dimensions and locations of penetrations were not known. As a result of this uncertainty, it was decided to construct the wall using block work to allow for penetrations to be more easily made when the building's equipment and services design was finalised. The project manager commented: *"The equipment contractors were directly contracted to [the client] and they were hard to pin down. So we always knew that product had to come through...so this issue has see-sawed back and forth with the issues that we have had with the openings."*

The local fire authority also played an important role, as it became apparent that the building design deviated from the specification standards contained in the BCA, necessitating approval of the fire wall design by the fire authority. Notwithstanding a decision to construct the building using fire retardant panels, the fire authority advised that they would not support the original building design because the design did not provide full perimeter access for fire appliances.

Once the plant and equipment design was finalised, the design team discovered that the penetrations required in the fire wall were considerably larger than the 600mm² allowed for in the existing block work wall. Not only would this necessitate re-work, but it would also compromise the fire integrity of the wall. Work commenced to enlarge the penetrations, presenting specific OHS risks to workers involved in demolishing sections of the block work wall. Once the plant was installed, the installation contractor then advised that the openings in the block work wall could have been 40% smaller in size.

To maintain the integrity of the firewall, the penetrations were in-filled to the recalculated sizing. However, this reconstruction had to take place after the fixed plant was already installed and workers had restricted access to the work area. The construction of the penetrations required that the block work be cut and the flashed with stainless steel to adhere to the food safety regulator's requirements. Whilst the openings were not high in

the wall, scaffolding was required to provide access.

The openings in the firewall remained a subject of contention. The fire authority maintained that the block work wall could no longer act as a firewall when it included penetrations. In the opinion of the fire authority, the building was an oversized single building that required a sprinkler system to comply with the BCA.

An assessment was commissioned from a fire engineer who advised that 'fire tunnels' would be required either side of the wall to stop the spread of fire, smoke and heat. The size (or length) of the tunnels was to be proportional to the size of the openings - the larger the opening, the longer the tunnel. However, limited space was available for the construction of fire tunnels as fixed plant had already been installed either side of the fire wall. The original design for the tunnel required a 2.5 metre length, for which there was insufficient space. A reduction in the size of the openings permitted a reduction in tunnel length to 1.8 metres. The construction of the fire tunnel commenced without the fire authority's approval, in order not to fall behind the project schedule. In the event, the fire authority did not approve this design, insisting on the installation of a full sprinkler system to the building. In order to obtain approval for the building design, the client agreed to retro-fit the building with a sprinkler system after the start-up of production.

The late inclusion of a sprinkler system into the design meant that the installation presented specific OHS challenges as workers needed to negotiate existing plant and services located in the ceiling, a confined space. Another area of OHS concern was access to the underside of the ceiling to install the sprinkler heads. Fixed plant and equipment had been installed in the building, which could not be moved to provide space for access equipment. Further, the production plant was operational when the sprinkler system was installed, providing only a short window of opportunity to carry out the work.

Case Two – Construction of a suburban train station platform

The second case arose during the design and construction of a suburban train station in Melbourne. As part of a major investment in public transport infrastructure the State Government of Victoria committed to the construction of a new railway station in an area of rapid population growth. A concept design was released and construction organizations were invited to tender for the design and construction of the station.

The original concept involved the construction of a new 'island' platform, built between two existing and fully functioning rail lines. A pedestrian footbridge was to be built, spanning the full width of the tracks. Access to the platforms from the footbridge was to be provided by stairs at either end and in the middle of the footbridge. In accordance with disabled access requirements, an alternative means of accessing the platform by provision of a lift was also included in the original concept design.

However, before the contract was awarded, an incident occurred at a similar rail station in Melbourne. This incident involved the death of a passenger who could not be removed safely from an island platform because the ambulance trolley would not fit in the

platform lift. Consequently, paramedics were forced to remove the passenger by walking over 'live' rail tracks.

Compounding concerns about access to and egress from station platforms was a growing number of passenger complaints about station lifts breaking down. A state election resulted in a new Liberal Government, which immediately initiated a review of design policy for rail stations. Requirements were introduced specifying that all new stations would be installed with lifts able to accommodate a standard ambulance trolley and an alternative means of access in the form of a ramp would also be provided. This new policy was introduced just two weeks after tenders closed for the railway station project and companies that had tendered for the project were given two weeks to amend their proposals.

The contract was eventually awarded to a design and construction contractor on the basis of a proposal that included a number of changes to the original concept design. The contractor considered that these changes would provide a quicker and more cost effective construction method, while also reducing the OHS risk to construction workers. For example, the platform structure was redesigned to reduce the number of supporting piers from three rows to two, with a cantilevered steel framed platform. This change increased the separation between the construction work zone and the 'live' train tracks, allowing trains to continue operating, providing a 'safety corridor' between trains and construction activities and reducing the frequency of exposure to hazards associated with the pier construction.

However, the late inclusion of a ramp in the design resulted in emergent hazards during the construction stage which were not envisaged at the tendering stage. A post-award risk assessment (involving the client, the rail operator and design and construction contractor) was conducted once the project commenced. This risk assessment focused primarily on the health and safety of passengers and the public, i.e. end users of the station. The risk of persons jumping over the ramp balustrading onto an adjoining canopy was identified as a major risk. The contractor commented: "*When we priced and sketched up [the proposed design] at tender stage, no ramp was included. We were only given two weeks. We had already put our price in and it was a last minute change by the client..... No one picked up at the time about the canopies being bisected [by the ramp]*". To address this risk, 'throw screens' were designed to be fixed to the ramp balustrading to reduce the risk of people climbing or throwing objects over the side. The risk assessment also identified the need to provide landings at regular intervals on the ramp to provide 'rest' areas.

The addition of the ramp, the landings and throw screens had a significant impact on the design and construction of the station. The sizing of columns supporting the ramp had to be substantially changed, with some columns more than doubling in size due to the inclusion of landings and throw screens. Size increases to the platform's steel structure were also required to safely support the increased loads associated with the ramp and larger columns. As a result of these changes, construction workers' exposure to hazards associated with crane lifts was significantly increased. Additional platform components needed to be lifted into place and the larger size of structural members reduced

manoeuvrability and increased risk. Workers' ability to control these lifts was a particular safety concern and the rail lines had to be closed on the days of the lifting operations. Further, the reduced clearance between the underside of platform beams, which had doubled in depth, and the ground meant that services originally planned to be connected to the underside of each beam had to be relocated due to restricted access clearances. Thus, a series of holes had to be cut into every intersecting beam for the length of the platform (approx. 100m), to allow conduit to be installed to accommodate services. The steel beams had been fabricated without any penetrations, so the in-situ cutting of holes presented new hazards associated with the use of cutting equipment in an area that was already difficult to access.

Case Three – Installation of a centrifuge in a sewerage treatment facility

The third case arose during the design and construction of sewerage infrastructure in the Australian Capital Territory. To ensure effective delivery of a long term, on-going capital works programme the client established an alliance with an external provider, with primary focus placed on renewal and upgrade of existing infrastructure. A review into the operation of existing facilities revealed that some of the pumping equipment no longer complied with legislative requirements, could not meet forecasted community demands and was infeasible to maintain and operate. The client organization developed a plan to upgrade four smaller sewerage pumps to three bigger pumps. The replacement of each pump was to be staggered over a 10 year period.

At the procurement stage of the project it became apparent that a centrifuge that was to be incorporated into the original design to replace two original pumps would not meet capacity requirements for the facility. Following a review of alternative options, a larger centrifuge that met all operational criteria was identified and purchased. The centrifuge was to be located on a mezzanine level of a pumping station with an adjoining void equal in height to that of a six storey building. Permanent edge protection was provided to the perimeter of the mezzanine, providing a safe work area. However, during installation it became apparent that, due to the size of the larger centrifuge, safe access to all areas of the centrifuge was not available. One end of the centrifuge butted up to the safety balustrading around the void, preventing access at this location. Access to all areas of the centrifuge was required to allow for ongoing maintenance of the facility. To reposition the centrifuge in the allocated space would require major alterations to equipment and infrastructure. To overcome the accessibility issue, a small purpose-built platform was designed to provide safe clearance and access to the end of the centrifuge, closest to the void. This design incorporated a steel platform attached to the edge of the concrete mezzanine floor which housed the centrifuge. This platform was to cantilever out over the void and would provide a safe 'walkway' around the perimeter of the centrifuge as well as providing a platform from which periodic maintenance of the centrifuge could take place.

A design brief was prepared by the project management team specifying the size, use and location of the platform and a structural engineer was engaged to design the platform. Access for the designer to measure and review the area was limited and so the platform

was designed to allow for some flexibility in its construction. This was achieved by incorporating joints that could be welded rather than having to rely on aligning bolt holes.

The installation of the platform created some specific challenges for the construction contractor. While a large portion of the platform was erected off site, access to the edge of the slab was still needed to fix the platform into position. Due to the height of the void and lack of any secure structure to 'tie in' the scaffold, a standard scaffold configuration, built from the ground up would have been unstable. A specialist scaffolding contractor was engaged to design and install a temporary cantilever scaffold, with hazards associated with working at heights identified as a major risk during scaffold erection and dismantling. Due to the size and weight of the partially completed platform, a crane was needed to move the structure into position. Existing plant and infrastructure sharing the work space severely hampered crane movements, increasing the risk associated with this activity. Damage to any of the existing infrastructure resulting from contact with the crane or the platform could have resulted in falling objects and/or exposure to hazardous substances. The requirement for on-site welding of the platform also elevated the risk to construction workers during the installation. Hazards associated with the welding included exposure to fumes and gases, burns, heat and noise. To mitigate the risks associated with welding, the construction workers were required to wear cumbersome protective clothing which, given that the work was carried out during the summer months and within close proximity to an industrial heater, presented new hazards associated with heat stress and fatigue.

Discussion

Tensions between construction and operational safety

The case examples reveal complexity inherent in construction design and the tensions that can emerge between designing a facility for safe construction and operation. In all three cases, design decisions that were taken in order to reduce health and/or safety risk when the facility was operational, resulted in increased OHS risk during construction. These examples illustrate how design decisions that improve OHS in one life cycle stage of a facility (e.g. operation/maintenance) do not automatically reduce OHS risks in other stages (e.g. construction) and may, in some circumstances, actually increase risk in some respects. Chinyio and Akintoye (2008) suggest trade-offs are an essential aspect of managing construction projects because the expectations of all stakeholders can rarely be achieved at the same time. Starr (1969) considered 'accepted' accident levels in society to be an indicator of society's preferred trade-offs between the risk and benefits of a hazard. Similarly, the case examples suggest that trade-offs between OHS in construction and end use are an unstated but inherent feature of design practice in the construction industry. Publications offering PtD guidance to construction design professionals currently say little about the potential for these tensions. It is very important that PtD policy documents and guidance notes provide practical guidance about how to identify and manage conflict (and possibly trade-offs) in reducing OHS risk across the life cycle of a facility.

Design instability

Design uncertainty and design change were key features of all three case examples. The cases reveal the emergent (and often unanticipated) nature of design-related hazards in construction projects, many of which relate to inherent uncertainty and/or changes to a design. This is consistent with Tryggestad *et al.* (2010) who demonstrate that design is a political and reflexive process of collective negotiation. In this context, uncertainty is prevalent and design goals are subject to change. The emergent nature of design-related OHS hazards illustrates problems associated with the application of standard OHS risk management protocols in the dynamic context of construction design. OHS risk management protocols assume that design is stable at a reasonably early stage and that all foreseeable hazards can be identified and subject to risk assessment and risk control. The lack of design stability in each of the case examples reveals problems inherent in the use of linear risk management methodologies to deal with PtD in construction projects. This is particularly well illustrated in the case of the train station project, in which the design and construction contractor's original proposal addressed issues of OHS during construction relevant to the original design concept. However, a post-award risk assessment, which focused primarily on the safety of end users of the facility, resulted in changes which introduced new, significant and unforeseen OHS hazards in the construction stage.

The role of external stakeholders

Another noteworthy feature of the case examples is the significant influence exerted by parties external to the project, whose actions substantially shaped design decisions (and their OHS consequences). In the case of the food processing facility, the local fire authority played a major role in shaping the design of the facility through their interpretation of the requirements of the BCA. In the case of the suburban rail station, the State Government of Victoria played a key role in the issue of new design requirements two weeks after the original tender for the project had closed. This finding is consistent with Olander (2007) who presents empirical evidence indicating that external stakeholders have a substantial impact during the planning and design stages of a construction project.

The role played by external stakeholders is often overlooked by proponents of PtD. The case examples reflect the need to understand construction design as a complex socio-technical system in which PtD outcomes emerge as a result of interactions between stakeholders. Olander and Landin (2008) argue that early acknowledgement of the interests of external stakeholders and the implementation of communication that is open, trustworthy, cooperative, respectful and informative can help to avoid project disruption. The early engagement of external stakeholders may also have avoided some of the OHS risks that emerged in our case study projects. Many external stakeholders are likely to have a greater interest in the operation of a facility, with the result that stakeholder influence in shaping designs could actually militate against decisions that would reduce the OHS risk experienced by construction workers. The role and interests of external stakeholders in shaping PtD outcomes in the construction industry deserves further analysis.

Conclusions

Development of PtD knowledge

The findings reveal the importance of understanding the emergent nature of design decision-making and the role of multiple stakeholders in negotiating design trade-offs (and PtD outcomes) in the construction industry. Previous PtD research has suggested technology-based tools to improve PtD outcomes, including decision support systems (Davison, 2003; Cooke *et al.*, 2008), visualisation (Hadikusumo and Rowlinson, 2004) and building information models (Toole and Gambatese 2008; Sulankivi *et al.* 2010; Kamardeen, 2010). If these tools are to be used effectively, it is important to understand the context and conditions which would support or impede their adoption. For example, it may be unrealistic to assume early design stability in certain circumstances. Further, the significant role played by external stakeholders (see also Olander 2007) suggests that stakeholder management strategies could be usefully applied to PtD in the construction context.

Implications for policy and practice

The analysis of these case examples raises the question of how best to identify and manage tensions that might arise between reducing OHS risk in the construction and operation/maintenance stages of a facility's life cycle. The question of what to do when a design solution to reduce OHS risk to end users of a facility will increase OHS risk to construction workers presents legal, ethical and practical problems. Recourse could be taken to the OHS legislation which, in Victoria at least, would suggest designers should focus their efforts on risk to the end users of a facility, though the inclusive wording of the ACT's legislation would not permit such a simple resolution. A practical risk management approach might lead decision-makers to consider the relative magnitude of the risk in each stage of the life cycle. For example, the length of exposure to a hazard in the operation/maintenance stage of a facility could be weighed against the relatively short term exposure to a hazard in the construction stage. Other considerations might reflect the ability of a construction contractor, relative to the ability of the general public to manage an OHS risk effectively. The question of voluntary versus involuntary exposure may also arise (See, also Slovic *et al.* 1980). However, there is an ethical dimension to these questions, which hinges on the acceptability, when thinking about PtD, of privileging end users' OHS at the expense of the health and safety of construction workers. The case examples suggest that the focus on end users is often driven by external stakeholders and, at least in Victoria, this appears to be reflected in the legislation. It is important that PtD policy-makers and practitioners recognise the potential for tension in designing for safety across the various life cycle stages of a facility. It is important that decision-makers engage in open consultation with all stakeholders (including constructors) and make explicit the basis for making trade-offs when these situations occur.

Limitations and future research

The research was limited by the number of case studies. We are unable to generalise the findings to the industry as a whole and make no attempt to do so. However, the cases demonstrate that decisions made to improve the safety of end users of a facility can, in some circumstances, impact negatively on the OHS of construction workers. The

research was also limited in its focus on trade-offs between OHS during construction and end use of a facility. There may also be significant impacts for deconstruction, demolition and/or the refurbishment of a facility. No attempt was made to evaluate the efficacy of any particular risk management approach or to consider the risk tolerance of relevant social groups (e.g. designers, construction workers and end users). Future research should address these issues. The question arises whether certain project delivery methods lend themselves to improved PtD outcomes. It is expected that integrated project delivery, early contractor involvement and collaborative forms of procurement would enhance the opportunity to identify design solutions that reduce OHS risk in both the construction and operation stages of a facility's life cycle. Research is ongoing in projects procured in a variety of different ways to investigate this proposition.

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