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The relationship between pre-construction decision-making and the effectiveness of risk control: Testing the time-safety influence curve

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Abstract

Purpose - The research explores the relationship between the timing with which decisions are made about how to control work health and safety (WHS) risks in construction project (i.e., either pre- or post-construction) and the quality of risk control outcomes.

Design/methodology/approach - Data was collected from 23 construction projects in Australia and the United States of America (USA). 43 features of work were identified for analysis and decision-making in relation to these features of work was mapped across the life of the projects. The quality of risk control outcomes was assessed using a classification system based on the 'hierarchy of control.' Within this hierarchy, technological forms of control are preferable to behavioural forms of controls.

Findings - The results indicate that risk control outcomes were significantly better in the Australian compared with the US cases. The results also reveal a significant relationship between the quality of risk controls and the timing of risk control selection decisions. The greater the proportion of risk controls selected during the pre-construction stages of a project, the better the risk control outcomes.

Research implications - The results provide preliminary evidence that technological risk controls are more likely to be implemented if WHS risks are considered and controls are selected in the planning and design stages of construction projects.

Practical implications - The research highlights the need for WHS risk to be integrated into decision-making early in the life of construction projects.

Originality/value - Previous research has linked accidents to design. However, the retrospective nature of these studies has not permitted an analysis of the effectiveness of integrating WHS into pre-construction decision-making. Prospective studies have been lacking. This research provides empirical evidence in support of the relationship between early consideration of WHS and risk control effectiveness.

Introduction

Safety in Design in the construction industry

The practice of anticipating and ‘designing out’ potential work health and safety (WHS) hazards associated with processes, structures and plant and equipment (referred to in this paper as Safety in Design, and is sometimes called “prevention through design”) has attracted considerable attention in recent years (Schulte, 2008) and has become a key feature of government policy in Australia (Creaser 2008). In the construction industry, the argument that the opportunities to reduce WHS risk are highest at the beginning of a project and become less and less as the project progresses is often cited (Toole, 2007). This contention is linked to the time-safety influence curve, developed by Szymberski (1997). The theoretical curve describes the relationship between the progression of a project through its composite phases (concept design, detailed design, procurement, construction etc.) and the ability to influence safety. The curve shows a rapid deterioration in the ability to influence safety as the project passes through the pre-construction stages. At the commencement of construction, the ability to influence safety is very low. This curve is almost universally cited by advocates of Safety in Design but, thus far, little empirical evidence exists to support it and divisions continue between those who dominate upstream (e.g. designers) and constructors and others downstream.

Aim

The current research sought to explore the validity of a variation of the time-safety influence curve, in particular by examining the extent to which there is a relationship between the *timing* of WHS risk control intervention and the *quality* of WHS risk control solutions. Specific objectives of the research were:

- To measure the quality of controls implemented to mitigate identified WHS hazards in case study construction projects using a newly developed “leading indicator” based on the hierarchy of control;
- To undertake a detailed evaluation of the point in time at which WHS risk control measures were selected for implementation; and
- To determine whether WHS risk control decisions made early in the project lifecycle, i.e. before the commencement of construction, are more likely to produce preferred controls for identified WHS hazards.

A general discussion of the growing appetite for Safety in Design is provided to establish the policy context for the research and a number of implementation difficulties are identified. Then previous studies linking design to construction accidents are discussed. The twofold need for prospective studies using an alternative measure of WHS as a dependent variable is explored. The hierarchy of control is presented as a useful alternative measure of the quality of WHS implementation. A case study research approach, implemented in the USA and Australia is described and the preliminary results arising from the research are presented and discussed. Conclusions are drawn as to the potential impact of Safety in Design on the effectiveness with which construction WHS risks can be mitigated.

Safety in Design policy and practice

In 1992 the Council of European Communities implemented the Directive 92/57/EEC - temporary or mobile construction sites. This directive established minimum safety and health requirements for temporary or mobile construction sites. The Directive required consideration of WHS during the design and organization of construction projects. A key feature of the Directive was the requirement to develop Health and Safety Plans in the pre-construction

stages of construction projects. The United Kingdom responded to the Directive with the enactment of the Construction (Design and Management) Regulations in 1994. The CDM Regulations were revised in 2007 and are currently undergoing further review and revision. Interest in creating WHS responsibilities for professionals engaged in the planning and design stages of construction projects subsequently grew outside the European Union. In Australia, for example, legislation requiring designers of buildings and structures to consider WHS in their decision-making has been implemented in all jurisdictions. While not a statutory requirement in the United States of America, 'Prevention through Design' has been the focus of a number of industry reports and initiatives (see, for example, Gambatese et al. 2005) and is a strategic goal cited in the *National Construction Agenda for Occupational Safety and Health in the US Construction Sector* (NORA Construction Sector Council, 2008). While the WHS Community has been pushing the concept, designers have been slow to "pull" WHS upstream, presumably due to litigious concerns.

Implementation problems in Design for Safety

Despite the growing momentum surrounding Safety in Design, practical implementation difficulties have been observed in construction projects. This partly relates to the level of Safety in Design knowledge and competency in the design professions. Brace et al. (2009) reviewed the causes of fatalities in the UK construction industry and report that "many designers still think that safety is 'nothing to do with me,' although there are a small cohort who want to engage and are having difficulty doing this because they do not fully understand what good practice looks like" (p. 12). In response to this finding, Donaghy (2009) recommended that accrediting bodies establish specific requirements to embed WHS in the education of all professionals engaged in the delivery of construction projects, including designers.

However, research also reveals some more structural impediments to the implementation of Safety in Design. In a review of the research literature, Swuste et al. (2012) comment, in-keeping with the time-safety influence curve, that the design phase of construction projects offers the greatest potential for safety to be positively influenced. However, Atkinson and Westall (2010) note that many design modifications implemented to improve WHS in construction represent fairly modest solutions. They cite examples of fixing rails or anchor points for fall arrest devices, which do not eliminate the inherently dangerous activity, i.e., working at height. 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. Swuste et al. (2012) state that 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 workers' behaviour (see, also Hopkins, 2006). It must also be recognized that at the construction stage, many contractors take pride in their perceived role to manage WHS decisions.

The case for Safety in Design

Many researchers have investigated the link between design and accidents in the construction industry. For example, in the USA, Behm (2005) undertook a review of 224 construction fatalities, finding that in 94 cases (42 per cent) the design could be linked to the fatal accident. A similar analysis of 100 non-fatal incidents in the UK construction industry revealed identified design as a contributing factor in approximately half of the cases (HSE, 2003). In Australia, Driscoll et al. (2008) reported 44 per cent of construction fatalities to be

“design-related.” Cooke and Lingard (2011) further examined data in the National Coroners’ Information System to explore the causal pathways leading from the design of a permanent building/structure to the immediate circumstances surrounding fatal accidents in the construction industry.

The need for prospective studies

These retrospective studies have been very useful in establishing the existence of some link between design work in the construction industry and WHS. However, the objective strength of the link remains unclear. Further, in focusing on outcomes (i.e, accidents), retrospective analyses tell us little about current situations that can impact future WHS performance. In order to better understand the relationship between pre-construction consideration of WHS and performance, prospective research designs are needed. Prospective studies in “live” projects permit the analysis of pre-construction WHS activity (as an independent variable) followed by the measurement of safety outcomes (as the dependent variable) in the construction stage.

Methods

Case study design

The research was part of a five year international benchmarking study of WHS in the construction industries of the United States of America and Australasia. The first phase of this research adopted a prospective case study approach (Orum *et al*, 1991; Eisenhardt, 1989; Fellows and Liu, 1997; Yin, 1994). Data were collected from a total of 23 construction projects, 10 of which were in Australia/New Zealand and 13 of which were in the United States of America. The research design attempted to sample across four major delivery systems and industry sectors. Thus, projects in the engineering, commercial/industrial building and residential sectors were selected. Owing to the fact that projects were drawn from various sectors of the construction industry, the scale (total cost) of the projects in the sample varied widely. However, as the purpose of the research was to explore the relationship between the timing of risk control decision-making and the nature of risk control outcomes, variation in the size of the project is unlikely to impact the results. One would expect that early decision-making would produce better risk control outcomes in small scale residential projects, as much as large scale engineering projects.

For each project, features of work were purposefully identified by project participants in consultation with the research team. Features of work were selected because they presented a particular WHS problem or challenge. In this embedded case study design, multiple features of work were selected from each construction project and the total number of features of work in the analysis was 43. The number of features of work from each construction projects ranged between 1 and 4 and the mean number was 1.9.

Data collection

For each feature of work, comprehensive data was collected to capture decisions that were made in relation to the design of the feature of work, the process by which it was to be constructed and the way that WHS hazards were to be addressed. Data were collected by conducting in-depth interviews with stakeholders involved in the planning, design and construction of the selected features of work. These structured interviews explored the timing and sequence of key decisions about each feature of work, and the influences that were at play as these decisions ‘unfolded’ in the project context. During the course of the research

288 interviews were conducted (185 in Australia and 103 in the USA). The average number of interviews per feature of work was 6.7.

Initially interviews were conducted with key project participants, i.e, the client, the principal design consultant and the construction contractors were interviewed. From these interviews, other project stakeholders were identified. These 'leads' were followed up until no further leads were provided. The number and identity of stakeholders varied from project to project but typically included end user representatives, design professionals and consultants, suppliers of materials or equipment, specialist subcontractors and external regulatory agencies.

The data collection protocol enabled the mapping of key decision points through the life of the construction project (including during the planning and design stages), information flows between stakeholders and the degree of influence each stakeholder had on decisions that were made. The methodology used to map these decisions has been previously described in Lingard et al. (2011).

The measurement of WHS

It is understood that measuring WHS using lagging indicators (such as lost time injury frequency rates) is relatively unhelpful. Lagging indicators measure the absence of safety rather than the presence of safety (Arezes & Miguel 2003; Lofquist 2010) and are thus not a direct measure of the level of safety present in a project. Further, even when there have been no accidents in a workplace, this does not necessarily mean that the workplace is safe (Cadieux et al. 2006). Stricoff (2003) observes that, even a stable safety system will produce a variable number of accidents. Measuring "near misses" is also not optimal. Thus, in evaluating the extent to which pre-construction WHS effort is linked to WHS, alternative "leading indicators" are preferred. Leading indicators of safety can be defined as indicators that change before the actual level of risk to which people are exposed changes (Kjellén, 2009). Leading indicators provide a more direct and proactive measure of how well an organization is managing WHS risk than the occurrence of accidents, which include an element of chance. In this research the quality of WHS risk mitigation was measured as a leading indicator, with reference to the 'hierarchy of control' (HOC) (Matthews, 1993).

Hierarchy of control

Arguably any evaluation of WHS practices should assess the quality and effectiveness of risk control outcomes (see also, Safe Work Australia, 2012).

The HOC classifies ways of dealing with WHS hazards according to the level of effectiveness of the control (Manuele, 2006, Haro and Kleiner, 2008). 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 and thus the worker is separated from the hazard. 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 in a sociotechnical systems perspective because they act on changing 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. These are 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 (PPE) is the least reliable of the control measures. Although, much emphasized and visible on a

worksite, at best, PPE should be seen as a “last resort,” see, for example Lombardi et al.’s analysis of barriers to the use of eye protection (Lombardi et al. 2009).

It is sometimes argued that Safety in Design is consistent with the implementation of higher order (technological) controls for WHS risk (see, for example, Gangolles et al 2010). However, little empirical evidence has been presented to support this claim.

Measurement of the dependent variable

The dependent variable of interest was the quality of risk control solutions implemented during the construction stage of the project.

For each feature of work (i.e, case) in the sample, WHS risks were identified. A common categorization scheme was developed based on the National Institute for Occupational Safety and Health (NIOSH) Occupational Injury & Illness Classification System (OIICS) (BLS, 2012). WHS risks relevant to each case were identified and categorized using this classification system (e.g., fall, slip, trip; struck by object or equipment, etc.).

Once WHS risks had been classified for each case, the methods by which each risk was actually controlled were identified. This information was elicited during the interviews and supplemented with site-based observations and examination of project documentation (e.g. plans and drawings). Thus, an attempt was made to verify the information provided during the interviews with on-site observation.

Methods of WHS risk control were classified according to their type. This classification was based on the hierarchy of control (HOC).

To ensure consistent classification of the WHS risk control measures, a detailed coding framework was developed. This coding framework identified the options available for controlling various WHS risks and provided the HOC score that should be given for each risk control option. The coding framework was used by two researchers who independently coded the data.

An average HOC score was generated for each feature of work, reflecting the quality of risk control solutions implemented for identified WHS hazards/risks. Each level of the HOC was given a rating ranging from one (personal protective equipment) to five (elimination). The risk controls implemented for hazards/risks presented by each feature of work were assigned a score on this five point scale. In the event that no risk controls were implemented, a value of zero was assigned. Using these values the mean HOC score for each feature of work was generated. Thus, if two hazards were identified, one was eliminated and the other controlled by administrative methods, the mean score would be 3.5.

To check the inter-rater reliability of the assessment, a subset of US cases was independently rated by the Australian research team and a subset of Australian cases was independently rated by the US research team.

Independent variable

Another variable captured during the data collection was the point in time at which a risk control “solution” was identified, i.e., whether this occurred in the planning stage, the design stage or the construction stage. The pre-construction interventions were collapsed into a single pre-construction category. Thus, the timing of a particular safety intervention was

dichotomously rated as occurring in the ‘pre-construction’ or the ‘construction’ stage of a project. For each case, the number of safety solutions implemented in the pre-construction stage was expressed as a percentage of the total number of safety solutions for that case. Thus, for each case, a value of the proportion of WHS risk control measures identified in the pre-construction (i.e, in the planning or design stages of the project) relative to the total number of control measures implemented was generated. This value was then used in further analysis as a proxy measure of the “pre-construction safety response” for each case.

Results

The sample

Table 1 shows a breakdown of the features of work (cases) by industry sector and delivery method. Features of work were drawn from the heavy engineering (39.6%), commercial (20.9%), industrial (27.9%) and residential (11.6%) sectors of the construction industry. The majority of cases were collected in projects procured using a Design and Build delivery mechanism (34.9%). Twelve cases (27.9%) were collected in accelerated project delivery arrangements. Nine cases (20.9%) were drawn from projects procured using a traditional (Design-Bid-Build) delivery method and seven cases (16.3%) were collected in projects using a collaborative delivery method.

Table 1: Features of work by sector and project delivery method

Case descriptor	Number of cases	Per cent
<i>Delivery method</i>		
Collaborative	7	16.3
Accelerated	12	27.9
Design-bid-build	9	20.9
Design and Build	15	34.9
<i>Sector</i>		
Heavy engineering	17	39.6
Residential	5	11.6
Commercial	9	20.9
Industrial	12	27.9

Table 2 shows the projects, features of work (cases) and the number of interviews conducted for each case included in the sample. The mean HOC score for each case is also presented.

Table 2: Summary of projects, cases, interviews per case and mean HOC score

Project	Number of Interviews for each case	HOC Mean Score	Case/Feature of work	Description
Centrifuge replacement for sewerage treatment facility	13	4.08	Installation of centrifuge	Removing 2 old centrifuges and installing one larger centrifuge to replace them
	13	3.73	Pipe works	Upgrading and installation of new pipes to connect the new centrifuge to the existing infrastructure
	9	2.44	Installation of a steel platform	Erection and installation of a steel platform over a void to provide access around the centrifuge for maintenance

Theatre demolition	8	3.08	Demolition	Demolition of a standalone lecture theatre to open up the area in preparation for future work
Public space landscaping	5	3.05	Landscaping	Landscaping an open square area using coloured artificial turf to create a geometric overlay
42-story residential Complex	6	4.25	Construction/installation of WRAP façade	Construction/installation of a self-supporting, architectural façade element with steel and RC members connected to the exterior of the building
	5	3.33	Construction of internal stair egress	Construction of a 'U' shape stair egress around the central building core with alternative landings between each floor to comply with fire regulations
Manufacturing facility	11	2.60	Roof and Wall Cladding	Installation of roof panels/sheets and skylights on roof structure, wall panels and openings
	8	4.50	Erecting/Installation of roof structure	Construction and installation of main spine trusses and trussed rafters for roof structure
	11	4.20	Erection/installation of steel columns	Erection/installation of four rows steel columns
	9	4.50	Construction of foundation system	Excavation and construction of pad foundations
Food processing plant reconstruction	8	3.56	Steel columns	Strengthening of the existing steel structure
	5	3.61	Sewerage disposal system	Installation of a new system for treatment/disposal of waste water with higher capacity and efficiency
	10	2.63	Fire wall	Construction of a fire wall as well as fire tunnels inside the production facility to comply with fire regulations
Cemetery mausoleum	8	4.19	Construction of basement mausoleum	Construction of basement mausoleum including excavation, temporary works, retaining walls, roof slab, finishing and mechanical works
Suburban train station	6	4.63	Construction of RC columns	Construction of RC columns supporting a pedestrian access bridge
	6	3.50	Construction of ramp access	Construction of a ramp accessing the platform
	6	4.31	Construction of platform and supporting columns	Construction of a concrete platform with steel frame and its supporting columns and foundation
Water pumping station upgrade	11	3.50	Construction of wet well	Construction and installation of an RC tank and pipework
	5	4.00	Construction of valve chamber	Construction of valve chamber including concrete walls and a base slab
Flood recovery works	8	2.73	Construction of a retaining wall on site 1	Data collection, clearing works, building access road on site 1 and construction of a gabion wall and its foundation
	8	4.25	Construction of a retaining wall on site 6	Data collection, clearing works, building access road on site 6 and construction of a gabion wall and its foundation
	6	4.25	Rectification of a pedestrian bridge	Installation of temporary works and elevation of a bridge deck over a creek
Football stadium	7	2.09	Foundation system	Excavation & Installation of micro-pile foundation system adjacent to existing parking garage and around existing utilities
	8	2.30	Steel superstructure	Demolition of existing stands and steel erection of new seating structures and press box

Psychiatric hospital	5	2.67	Exterior pre-cast concrete panels	Lift and place of pre-cast concrete panels on exterior and attachment to structural steel
	6	2.38	Roof structure and barricades	Installation of roof membrane and construction of permanent roof barricades around HVAC
House construction	2	2.36	Exterior structures (basement, exterior walls, roof)	Pre-fabrication and construction of exterior & interior walls and roof structure
Wastewater tank	9	2.50	Pre-stressed concrete steel tank	Excavation and shoring of tank location and construction of pre-stressed concrete tank
	9	2.25	Sewer trunk line across creek	Installation of sewer trunk line across creek from barge using divers
House construction	3	2.62	Exterior structures (basement, exterior walls, roof)	Site excavation, installation of pre-formed concrete basement, and construction of exterior walls and roof structure
Server farm	3	2.40	Demolition of existing structure	Demolition of existing one-story structure and separation of waste and recyclables for LEEDS
	4	2.33	Gas fire suppression system	Installation of tanks, actuator valves, and distribution pipe for gas fire suppression system
College cafeteria	5	2.29	Foundation system	Excavation of site and construction and backfill of front retaining wall
	6	2.42	Steel superstructure	Delivery of steel beams and lift and place of steel structure around two adjacent buildings
Chemical plant upgrade	5	3.17	Steel structure for new equipment	Pre-fabrication of steel structure for new equipment and tie-in to existing plant infrastructure
Road reconstruction	6	2.60	Maintenance of traffic	Maintenance of traffic plan during reconstruction of 6-lane highway and repavement of adjacent side streets
	6	2.50	Utility replacement	Excavation and condemnation of existing utilities and installation of new utilities
Bridge Reconstruction	4	1.73	Maintenance of traffic	Maintenance of traffic during removal of existing asphalt and installation of new asphalt on one lane of 4-lane bridge
New Interstate	6	2.64	Maintenance of traffic	Maintenance of traffic on haul roads, temporary bridges, and public roads
Hospital	4	2.78	Steel superstructure	Lift and place of steel beams for structure
	4	3.00	Internal systems	Pre-fabrication of internal walls and installation of electrical and mechanical systems in building
House	1	2.56	Exterior structures (basement, exterior walls, roof)	Site excavation, installation of pre-formed concrete basement, and construction of exterior walls and roof structure

Inter-rater reliability

In order to ensure that researchers' coding of risk controls into the five level HOC categories was consistent between the US and Australian datasets, a coding framework was developed that specified HOC ratings for common responses to different hazard "types." This served as a basis for reducing variance between the ratings. Further, a follow-up inter-rater reliability check was performed after each country had finalized their data coding. A list of safety challenges and implemented risk controls from one case were sent from the Australian to the US research team (and vice versa). Each group then rated the others' sample data using the HOC classification method. The US rater's HOC classification was consistent with the Australian research team classifications in 12 of 14 Australian cases (85.7%). The Australian rater's HOC classification was consistent with the US research team classifications in 9 of the 10 US cases (90%). The high level of agreement suggests that the HOC classification method was applied consistently between the two countries.

Descriptive statistics

Table 3 shows the mean HOC scores for cases by industry sector, project type and country. Australian cases in the analysis had higher average HOC scores than were evident in the US cases. Further, the difference between mean HOC scores between the US and Australian cases was found to be statistically significant ($t=7.731$, $p=.001$). Cases embedded within projects delivered using collaborative or design and build delivery methods had slightly higher HOC scores than cases embedded within projects delivered using an accelerated (fast track) or design-bid-build delivery approach. Cases embedded in commercial and residential construction projects had lower mean HOC scores than cases embedded in projects within the engineering and industrial construction sectors. However the differences in HOC scores were not significantly different between cases embedded in projects using different delivery methods or in different industry sectors.

Table 3: Mean HOC scores by country, project delivery method and industry sector

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

Early consideration of WHS and risk control outcomes

Figure 1 shows the relationship between the extent to which WHS risk controls were considered and decided upon before commencement of construction (i.e., in the planning or design stages of the project) and the quality of risk control outcomes (i.e., the average HOC score). Figure 1 shows a positive relationship between the consideration of WHS in the early stages of a construction project and the eventual implementation of higher order (i.e. technological) risk controls in the construction stage. A Pearson product moment correlation revealed this relationship to be statistically significant ($r=.737$, $p=.001$).

Figure 1: Linear relationship between the pre-construction WHS intervention the mean HOC score

Discussion

The timing of risk control interventions

Our research provides some evidence for the link between early intervention in WHS (in the pre-construction stages of the project life cycle) and the implementation of higher order controls for WHS risk. This is important new knowledge because it lends preliminary support to the validity of the Szymberski's time-safety influence curve. If the underlying premise of the HOC is accepted, i.e., technological controls are more effective than behavioural controls for WHS risk, our research can partially explain the shape of the theoretical time-safety influence curve. The slope of the curve, depicted by Szymberski and reproduced by many others, indicates that the ability to influence safety decreases dramatically during the pre-construction stages of a construction project. Once construction commences the ability to influence safety is fairly low, but the rate of decline also slows, i.e. the curve levels.

The results indicate that it is statistically more likely that technological risk controls (i.e., elimination, substitution and engineering controls) will be implemented if WHS is considered in the pre-construction stages of a project and risk control decisions are taken in these early stages. Assuming that technological risk controls will have a greater risk reduction effect, our results support the notion that the ability to influence safety would be substantially lower if consideration of WHS (and selection of risk controls) was left until the construction stage had commenced.

Implications for practice

The research suggests that the early consideration of WHS risks in construction project decision-making is associated with the realisation of more effective (i.e., “higher order”) controls in the HOC. As higher order controls tend to be technology-based and make the work environment safer, these are preferred forms of WHS risk control. In contrast, if left until immediately prior to the commencement of construction, attempts to control WHS risk are more likely to be behavioural (or “lower order”) controls. These controls are less reliable than technological controls because humans are fallible. Human error is an inevitable characteristic of industrial systems, and a common feature of construction accident causation. Thus, wherever possible, systems should be designed to make the work environment inherently safe, such that errors do not result in accidents. This principle underpins the thinking behind “Safety in Design” which seeks to use technological solutions to proactively design WHS hazards out of workplaces and processes wherever possible.

Implications for research

Our research also highlights the potential usefulness of prospective research designs in evaluating the strength of the link between the integration of WHS into decision-making in project planning and design and the WHS effectiveness. The retrospective investigation of design as a causal factor in past accidents has been very useful to the extent that it has provided some evidence of a link between design and safety. However, retrospective studies have not addressed the extent to which the consideration of WHS prior to construction (i.e., in the planning and design stages of projects) can actually deliver improved WHS outcomes in subsequent project stages. Also, inherent in the retrospective analysis of accident causes is the possibility that the relationship between design and accidents might be over-stated by researchers who are actively looking for “design relatedness” - a phenomenon referred to by Lundberg et al. (2009) as “what-you-look-for-is-what-you-find.”

The prospective “live” case study approach adopted in this research is useful in determining the strength of the relationship between the pre-construction consideration of WHS and the subsequent quality of WHS outcomes in construction projects.

Our research also developed a new method for measuring the dependent variable, i.e., WHS performance. Rather than measure the occurrence of accidents, which is a notoriously unreliable and rare measure of safety performance in construction projects, we opted to use a new ‘leading indicator’ of WHS performance. In using the HOC to measure the quality of the risk mitigation effort for each case in the analysis, we more directly measured the quality of WHS risk management.

Conclusions

The research provides preliminary empirical evidence in support of the positive benefits of considering construction workers' WHS when making decisions in the planning and design stages of construction projects. The statistical results suggest that when hazards are identified and risk control measures are chosen in the early stages of a construction project, they are more likely to be of a higher order, technological nature, than when WHS is not considered until construction work commences. The prospective nature of the research enabled the strength of the link between early intervention with regard to WHS and risk control outcomes. It is recommended that similar prospective designs be used in future studies seeking to quantitatively evaluate the link between Safety in Design and WHS in the construction industry. Further, the use of a leading, as opposed to lagging indicator of WHS represented a more direct measure of the dependent variable (i.e, WHS outcomes) than has been used in previous studies. The research highlights the importance of encouraging project participants engaged in the planning and design stages of construction projects to identify the WHS implications of their decisions and consider ways to eliminate or reduce WHS risks using technological control measures (i.e, by implementing elimination, substitution or engineering controls) when practical and conceivable.

Limitations and future research

Despite producing new evidence to support the oft-cited time-safety influence curve, this research was limited in a number of respects. First, no attempt was made to identify the precise timing of the risk control interventions in the pre-construction stages. The reason for this is that the duration of the planning and design stages for each case study project were different and, the different project delivery mechanisms created varying degrees of overlap between stages and activities. Consequently our measurement of the timing of the WHS intervention was "blunt." A more fine-grained analysis of the relative timing and effectiveness of WHS risk control interventions would permit the shape of the time-safety influence curve to be more precisely defined.

We also "pooled" our projects to evaluate the relationship between the timing of risk control decisions and the type of risk controls implemented. Our sample included projects from different industry sectors that valued considerably in scale and cost. Unfortunately we did not have sufficient numbers of projects to evaluate whether the relationship between the timing of risk control decisions and the type of control measures realised differs between projects of varying size and scale.

Future research will focus on developing the risk control hierarchy response as a leading indicator for use in construction WHS research. This will include the further development and validation of a robust set of guidelines/rules for the classification of specific WHS risk controls. The extent to which the HOC "score," as a leading indicator, can predict the occurrence of accidents (a lagging indicator) at a future point in time. The use of Building Information Modelling as a tool for design and planning stage to facilitate consideration of higher order HOC solutions is also to be pursued.

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