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Received 11 August 2013
Revised 7 April 2014
Accepted 3 July 2014

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 purpose of this paper is to explore 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 were collected from 23 construction projects in Australia and the USA. Totally, 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 limitations/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.

Emerald

Engineering, Construction and Architectural Management
Vol. 22 No. 1, 2015
pp. 108-124
© Emerald Group Publishing Limited
0969-9988
DOI 10.1108/ECAM-08-2013-0074

Keywords Design and development, Decision making, Health and safety, Pre-construction, Planning and control
Paper type Research paper

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 sometimes called "prevention through design") has attracted considerable attention in recent years (Schulte, 2008). Safety in Design 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, suggesting 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 expected to be very low. The time-safety influence 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 an adaptation 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 effectiveness of WHS risk control solutions. Specific objectives of the research were:

- to measure the effectiveness of WHS hazard/risk controls in case study construction projects using a newly developed leading indicator based on the hierarchy of control (HOC);
- 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 life cycle, i.e. before the commencement of construction, are more likely to produce effective controls for WHS hazards/risks.

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. Previous research linking design to construction accidents is discussed. The twofold need for prospective studies using valid and reliable measures of WHS effectiveness is described. The HOC is presented as a useful measure of the effectiveness of WHS interventions. A case study research approach, implemented in the USA and Australia is described and preliminary results arising from the research are presented and discussed. Conclusions are drawn as to the relationship between the timing of Safety in Design activities in the life of a construction project and the effectiveness of WHS risk mitigation.

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 UK 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 USA, "Prevention through Design" has been the focus of a number of industry reports and initiatives (see, e.g. 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* (National Occupational Research Agenda 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.

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 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 (Health and Safety Executive, 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 a link between design and WHS in the construction industry. However, the objective strength of this 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 WHS 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 USA and Australasia. The 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, ten of which were in Australia/New Zealand and 13 of which were in the USA.

The research design involved replication and cross-validation of across two diverse and different samples (i.e. the US and Australia/New Zealand project samples).

The relationship between the timing of Safety in Design decisions and the effectiveness of WHS risk control were evaluated in the Australian and the American data independently. This replication in two samples drawn from industries with different industrial climates and regulatory contexts enables stronger conclusions than had the research been undertaken within a single context.

The sample was drawn from four major delivery systems and industry sectors. Owing to the fact that projects were drawn from various sectors of the construction industry, the scale of the projects in the sample varied. However, as the purpose of the research was to explore the relationship between the timing of risk control decision making and the effectiveness of risk control outcomes, variation in the size of the project was unlikely to impact the results. One would expect that early decision making would produce more effective risk control outcomes in small scale residential projects, as much as large scale engineering projects.

For each construction 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. Multiple features of work were selected from each construction project. The total number of features of work included 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 per project.

Data collection

Data were 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 hazard/risks were mitigated.

In-depth interviews were conducted with stakeholders involved in the planning, design and construction of each feature of work. Interviews explored the timing and sequence of key decisions, 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 contractor. From these interviews, other project stakeholders were identified. These "leads" were followed up until no further leads were provided. The number of interviews varied from project to project but interviewees typically included end user representatives, design professionals and consultants, suppliers of materials or equipment, specialist subcontractors and external regulatory agencies.

The measurement of WHS

Measuring WHS using lagging indicators (such as accident frequency rates) is unhelpful. Lagging indicators measure the absence of safety rather than the presence of safety and do not constitute a direct measure of the level of WHS in a work system (Arezes and Miguel, 2003; Lofquist, 2010). Even when there have been no accidents, this does not necessarily mean that a workplace is safe and that WHS risks are being controlled effectively (Cadieux *et al.*, 2006). Accident rates are susceptible to random variation and Stricoff (2000) observes that, even a stable safety system will produce a variable number of accidents.

There is a growing interest in the usefulness of "leading indicators" of WHS (Kjellén, 2009). Leading indicators change before the escalation of WHS risk or the occurrence of accidents and are believed to more directly measure how well an organization is managing WHS. In this research the effectiveness of WHS control was measured as a leading indicator, with reference to the "HOC".

HOC

Arguably any evaluation of WHS interventions should assess the quality and effectiveness of risk control as a dependent variable (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 workplace and no longer poses a threat to health or safety. If elimination is not possible, the next best option for risk control is substitution. This involves replacing something that produces a hazard with something less hazardous. Beneath substitution in order of preference are engineering controls, i.e. controls that physically isolate workers from hazards. The top three layers of the HOC (i.e. elimination, substitution and engineering) are classed as technological in nature because they change the physical work environment. In contrast, the bottom two layers of the HOC represent behavioural controls that seek to change the way people work. These are administrative controls, which include such measures as implementing safe work procedures or a job rotation scheme to limit exposure to a hazard. The lowest level of control in the HOC is personal protective equipment (PPE). Although, much emphasized and visible on a worksite, at best, PPE should be seen as a "last resort". Lombardi *et al.* (2009) provide an analysis of barriers to the use of eye protection which provides insight into the problems inherent in relying on PPE as a risk control measure (Lombardi *et al.*, 2009).

Measurement of the dependent variable

It is sometimes argued that Safety in Design is consistent with the implementation of higher order (technological) controls for WHS risk (see, e.g. Gangolells *et al.*, 2010). However, little empirical evidence has been presented to support this claim. The present research used the HOC to test this proposition.

The dependent variable was the effectiveness of measures implemented in the case study construction projects to mitigate WHS hazards/risks. For each feature of work in both the US and Australia/New Zealand samples WHS hazards/risks were identified. A common categorization scheme was developed based on the National Institute for Occupational Safety and Health, Occupational Injury & Illness Classification System (Bureau of Labor Statistics, 2012). WHS hazards/risks relevant to each case were identified and categorized using this classification system. Classification was based on known hazards/risks inherent in construction activities relating to a given feature of work, for example, features of work involving *in situ* blockwork were classified as presenting a manual handling hazard/risk.

Once WHS hazards/risks had been identified and classified for each feature of work, the methods by which each hazard/risk was 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). Next, the WHS risk control solutions implemented for each identified hazard/risk were classified according to their type. This classification was based on the 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 specific WHS hazards/risks (i.e. elimination, substitution, engineering, administrative and PPE controls). The coding framework was used by two researchers (one from the USA and one from Australia) who independently allocated an HOC code to each control identified for a given WHS hazard/risk.

Each level of the HOC was given a rating ranging from one (PPE) to five (elimination). The WHS hazard/risk controls implemented for each feature of work in both US and Australia/New Zealand samples were assigned a score on this five-point scale. Using these values, an average HOC score was generated for each feature of work. Thus, if two hazards were identified, one was eliminated and the other controlled by administrative methods, the mean score would be 3.5. In the event that no risk controls were implemented, a value of zero was assigned.

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

Independent variable

The relevant independent variable for this analysis was the point in time at which a hazard/risk control solution was selected, 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 WHS 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 feature of work, the independent variable reflected the number of WHS hazard/risk control measures decided upon in the pre-construction (i.e. in the planning or design stages of the project) as a percentage of the total number of WHS hazard/risk control measures implemented. 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 I shows a breakdown of the features of work (cases) by industry sector and delivery method. Cases were drawn from the heavy engineering (39.6 per cent), commercial (20.9 per cent), industrial (27.9 per cent) and residential (11.6 per cent) sectors of the construction industry. The majority of cases were collected in projects procured using a Design and Build delivery mechanism (34.9 per cent). Totally, 12 cases (27.9 per cent) were collected in projects governed by accelerated project delivery arrangements. Nine cases (20.9 per cent) were drawn from projects procured using a traditional (design-bid-build) delivery method and seven cases (16.3 per cent) were collected in projects using a collaborative delivery method.

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

Table I. Features of work by sector and project delivery method

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

Inter-rater reliability

In order to ensure that researchers' coding of WHS/hazard risk controls into the five level-HOC schema was consistent between the US and Australian data sets, an inter-rater reliability check was performed after each country had finalized their data coding. A list of WHS challenges and implemented hazard/risk controls from one construction project were sent from the Australian to the US research team (and vice versa). Each group then rated the others' data using the HOC classification and coding method. The US rater's HOC classification was consistent with the Australian research team classifications in 12 of 14 Australian cases (85.7 per cent). The Australian rater's HOC classification was consistent with the US research team classifications in nine of the ten US cases (90 per cent). The high level of agreement suggests that the HOC classification method was applied consistently between the two countries.

Descriptive statistics

Table III 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 ($t = 7.731$, $p = 0.001$). 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.

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 ($r = 0.737$, $p = 0.001$).

Discussion

The timing of risk control interventions

Our research provides some evidence for the link between early intervention in WHS, especially in the pre-construction stages of the project life cycle, and the implementation of preferred technological controls for WHS hazards/risks. 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

Table II. 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

(*continued*)

Table II.

Project	Number of interviews for each case	HOC mean score	Case/feature of work	Description
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

(*continued*)

Table II.

Project	Number of interviews for each case	HOC mean score	Case/feature of work	Description
Football stadium	7	2.09	Foundation system	Excavation and 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 and interior walls and roof structure
Waste water 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

(*continued*)

Project	Number of interviews for each case	HOC mean score	Case/feature of work	Description
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 re-pavement 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

Table II.

Table III.
Mean HOC scores by country, project delivery method and industry sector

Case descriptor	Mean HOC score	SD
Country		
USA	2.48	0.311
Australia	3.69	0.671
Delivery method		
Collaborative	3.36	0.632
Accelerated	2.98	0.820
Design-bid-build	2.71	0.602
Design and build	3.38	0.233
Sector		
Heavy engineering	3.33	0.844
Residential	3.02	0.777
Commercial	2.72	0.649
Industrial	3.13	0.807

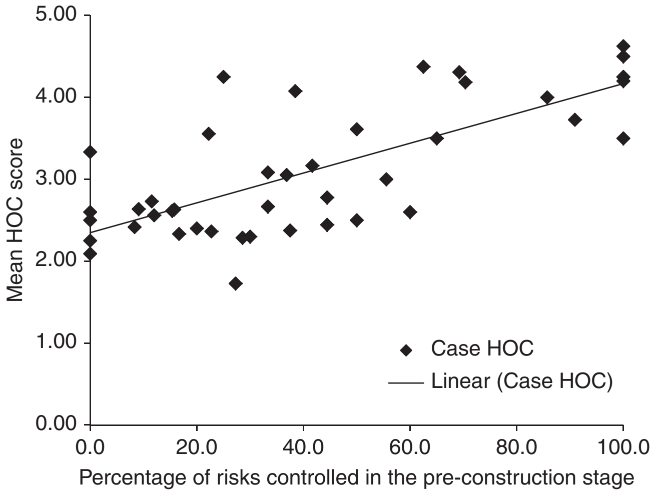

Figure 1.
Linear relationship between the pre-construction WHS intervention the mean HOC score

mitigating WHS hazards/risks, 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 WHS decreases dramatically during the pre-construction stages of a construction project. Once construction commences the ability to influence WHS 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 and risk control decisions are taken in the early pre-construction stages of a project. Assuming that technological risk controls will have a greater risk reduction effect, our results support the notion that the ability to influence WHS would be substantially lower if consideration of WHS (and the selection of hazard/risk controls) was left until construction work has commenced.

Implications for practice

The research suggests that the early consideration of WHS hazards/risks in construction project decision making is associated with the realization of more effective methods of risk control. As higher order controls are technology based and make the work environment physically safer and healthier, these are preferred forms of WHS hazard/risk control. In contrast, if left until immediately prior to the commencement of construction, attempts to control WHS hazards/risks are more likely to be behavioural 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. Wherever possible, workplaces and processes, plant and equipment, should be designed to make the work environment inherently safe, so that errors do not result in accidents. This principle underpins the thinking behind Safety in Design which seeks to proactively design WHS hazards and out of workplaces, processes plant and equipment wherever possible.

Implications for research

Our research also highlights the potential usefulness of prospective research designs in assessing how strong the link between planning and design decision making and overall WHS effectiveness actually is. 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 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 effectiveness of action taken to mitigate WHS hazards/risks.

Our research also developed a new method for measuring the dependent variable. Rather than measure the occurrence of accidents, which is a notoriously unreliable and rare measure of WHS performance in construction projects, we opted to use a new "leading indicator". In using the HOC to measure the effectiveness 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 sheds light on the strength of the link between early intervention and WHS hazard/risk control outcomes. Further, the use of a leading, as opposed to lagging indicator of WHS provided a more direct measure of the dependent variable 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 when practicable.

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. Also, 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 rather "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 HOC outcomes differ significantly between projects of varying size and scale.

Future research will focus on developing the HOC classification 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 relationship between the HOC scoring and lagging indicators will be examined.

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