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Supporting the Design OHS Process: A Knowledge-Based System for Risk Management

Helen Lingard  
Andrew Stranieri  
Nick Blismas

INTRODUCTION

Design OHS

According to theories of risk management, the most effective way to manage a risk is to eliminate or reduce it at source. Within the construction industry, this “source” is the design team (Martens 1998) and there is compelling evidence to suggest that decisions made during the design stage of a project can have a significant impact upon occupational health and safety (OHS) during the construction, occupation, maintenance and demolition stages of a building’s lifecycle (Williams 1998; Commission of the European Communities 1993). Construction design professionals have considerable opportunity to eliminate or reduce OHS risks throughout the lifecycle of the buildings or structures they design. Designers make choices about the methods of construction and materials used, which can significantly impact upon the OHS of those who build, occupy, maintain, clean, renovate, refurbish or eventually demolish a building or structure (European Construction Institute (ECI) 1996; Hinze & Gambatese 1994).

The importance of design OHS has been recognised by policy-making bodies and legislators, in Australia and elsewhere. The Australian National Occupational Health and Safety Commission (NOHSC 2002) identified design as a critical factor in occupational injuries and fatalities, and established design OHS as an area of national priority in the National OHS Strategy 2002–2012 (NOHSC 2002). Specific obligations for construction designers have been included in the preventive OHS legislation in four Australian states (Western Australia, South Australia, Queensland and Victoria (Bluff 2003)) and the adequacy of designers’ OHS responsibilities is an issue currently under review in New South Wales.

However, enactment of such legislation does not automatically deliver a reduction in OHS risk. The case of the UK’s OHS design legislation, enacted in 1995, reveals that there is a fundamental lack of knowledge and appreciation among designers surrounding the OHS consequences of their designs (Summerhayes 2002). Further research suggests that the majority of UK designers do not treat OHS as a priority and design risk assessments are of poor quality (Rigby 2003; Entec 2000). Likewise, it is doubtful that Australian construction designers are, at present, sufficiently well informed about ways in which OHS risks arising as a result of their design can be identified, assessed and controlled. Australia is therefore in a position to learn from the experience of the UK, and develop tools that help construction designers to better integrate OHS risk management into the design process.

This chapter presents the conceptual design for an innovative IT application that is being developed to assist construction designers to integrate OHS into their design decision-making. It describes the mechanism by which OHS knowledge will be modelled and presented to design professionals.

Knowledge-based systems in occupational health and safety

Knowledge-based systems (KBSs) seek to replicate, by computer, the problem-solving expertise of human specialists in a specific area of application. KBSs are ideally suited to providing OHS decision support because OHS is a specialist area in which it is undesirable to learn from one’s mistakes. The deployment, through software, of OHS expertise that would otherwise be unavailable to the decision-maker can be of considerable benefit in the management of OHS (Roberston & Fox 2000). Two ways in which KBSs have been successfully used to aid OHS decision-making are in the provision of regulatory advice and in supporting the OHS risk-management process. Given the lack of OHS expertise among construction designers, a knowledge-based decision support application has considerable potential to ensure that designers integrate OHS risk management into their design decision-making.
Knowledge-based systems in design

Knowledge-based decision support tools have previously been demonstrated to improve decision-making and enhance the efficiency and productivity of designers. For example, Berrais (2005) describes a system for the provision of expertise relating to the design of earthquake-resistant reinforced concrete buildings. This system ensures that designers who have little or no experience in earthquake zones are able to consider all of the relevant factors in their design decision-making.

Knowledge-intensive computer-aided design (KIC) systems have also been developed to provide knowledge that has a bearing on the design process accessible to designers (Mantyla 1995). KIC systems have been used to provide expertise, standards and regulations relevant to the resolution of design problems. For example, Yip et al. (2005), deployed machine learning algorithms to model the airflow and heat retaining properties of toaster cases and predict the performance of a newly designed toaster, thus obviating the need for a physical prototype. Likewise, the Building and Construction Authority of the Singapore Government has applied artificial intelligence techniques for the automated assessment of plans against building regulations in a system known as CORENET. In CORENET, building elements are represented using the International Alliance for Interoperability’s (IAI) industry foundation classes (IFC) and include rooflights, vertical windows and roof slabs. The CORENET knowledge base represents building regulations as rules that apply to building entities and their properties. During an automated plan-checking session, the rules associated with each building entity are interrogated in order to identify breaches of the building regulations.

Davison (2003) reports on the development of a prototype that deploys a similar automated plan-checking technology to provide knowledge-based advice on OHS in building design. Elements are encoded as IFCs but, rather than apply building regulation rules to identify breaches, OHS rules are applied to identify risks inherent in the use of each building entity. A designer using this prototype can initially view textual information, including relevant legislation, regulations and cases. Then, risks associated with the building’s lifecycle (including construction, maintenance, use and demolition) are identified and assessed during a rule-checking phase. This British prototype uses a large number of “if … then” rules as the basis upon which to solve problems.

The chapter briefly describes the research and development (R&D) process being used to deliver the Australian design OHS decision support prototype, before focusing on the novel method of modelling OHS knowledge that will be deployed. The advantages of this novel knowledge representation approach over traditional rule-based systems (such as those deployed by Davison (2003) and in the Singaporean CORENET system) are discussed.

The prototype development process

An R&D project is currently under way to develop a prototype tool to provide practical, user-friendly OHS advice, enabling designers to manage the risk of falls from height arising from their design decisions. The project will:

- develop a model of best practice reasoning used by building designers when assessing and reducing the OHS risk posed by their designs — the model will initially be limited to the risk of falls from height during the use and maintenance stages of a building’s lifecycle
- implement the model as a web-based decision-support system — designers will step through a sequence of questions about their design, and the system will make an assessment of falls from height risks associated with a design
- trial the decision-support tool among a sample of construction design professionals and evaluate the outcomes.

The R&D project is being carried out in the three stages briefly described below.

**Stage 1: Knowledge acquisition**

This stage involves collecting the data that will underpin the decision-support tool. Teams of experienced construction designers will participate in workshops facilitated by an OHS expert. Workshops will also be attended by groups of facilities managers, representing building users and maintenance personnel to ensure that the OHS risk experience and knowledge of these parties is adequately captured. The workshops will seek to:

- identify “falls from height” hazards introduced by design decisions
- assess the OHS risk presented by these “falls from height” hazards
- provide advice as to how the risk of falling from height could be reduced through design modifications.

Once collected, this knowledge will be structured to create a series of “argument trees.” These trees represent the hierarchy of factors which are believed (by the experts involved in the Stage 1 workshops) to be relevant to the determination of OHS risk and the choice of risk-control measure. These argument trees represent the expertise that will form the basis of the decision-support tool and it is critical that all relevant factors are represented. Prior to the development of the decision-support tool, the argument trees will be validated. The argument trees will be presented to a second group of experts to ensure that all the relevant factors that need to be considered in the risk assessment and control decisions of construction designers are reflected. The argument trees will be modified as necessary until consensus is reached.
Stage 2: Prototype development
A prototype decision-support tool will be “built.” Initially, within the scope of this project, a stand-alone tool will be delivered, but it is envisaged that eventually the decision-support application will be linked to computer aided design (CAD) applications, such that designs created in CAD applications can be “uploaded” and subject to an automatic on-line risk assessment. Designers will then be alerted as to those OHS risks that exceed a threshold value and prompted to reduce these risks according to preferred options in the “hierarchy of controls.” This hierarchy arranges OHS measures in order of priority from the most effective to the least effective.

Stage 3: Evaluation of the prototype
Finally, a group of construction designers will be required to use the tool and undertake a formative evaluation of its impact. The evaluation will consider issues of user-friendliness, practical benefit and the extent to which the tool results in practical risk reduction for falls from height. In determining the tool’s potential to reduce OHS risks, a group of building users, facilities managers and maintenance workers will perform a post hoc evaluation of design decision-making in a series of case study projects.

INNOVATION IN KNOWLEDGE MODELLING

Limitations of rule-based systems
Despite the excitement surrounding the development of early expert systems, the commercial deployment of rule-based knowledge-based systems has been problematic. Reasons for this lie partly in the fact that such systems are often cumbersome and slow. Rule sets that underpin real-world problems are typically large (10,000 rules is not exceptional) and difficult, and time-consuming to elicit from experts. The development of many early expert systems was halted because of the enormous time required by knowledge engineers to interview experts, translate their knowledge into rule sets and validate the resulting rules. Lenat (1983) coined the phrase “knowledge acquisition bottleneck” to describe this problem. Associated with the large number of rules required to adequately represent factors influencing real-world decision-making was the speed of early, rule-based knowledge-based systems. Inference engines that chain through large rule sets rapidly enough for real-time and even web-based applications are very difficult to develop.

Problems also arise as a result of the fact that real-world problems are often too complex to be adequately represented in the form of simple “if … then” rules. Rule sets do not easily encode uncertain or discretionary knowledge and inference engines do not elegantly infer with uncertainty attached to rules. The issue of “open texture” (i.e. the indeterminate nature of concepts) presents a particular problem in the use of rules to represent knowledge relating to legal reasoning and compliance.

Although rule-based knowledge-based systems have made a significant contribution towards the development of computational models of reasoning, it is now widely accepted that reasoning represented as rules is applicable only in highly structured and narrowly contextualised situations. Consequently, knowledge-based systems which represent knowledge as rules are not well suited to the application of OHS because the management of OHS risk is characterised by professional judgment and discretionary decision-making.

Design OHS legislation
OHS legislation provides duty holders with considerable discretion. Flick (1979) defines discretionary domains as those in which in which a decision-maker has the freedom to select one interpretation or outcome from a number of permissible options. Dworkin (1977) proposes two basic types of discretion, which he calls strong and weak discretion. Weak discretion describes situations where decision-makers must interpret standards in their own way, whereas strong discretion characterises those decisions in which decision-makers are not bound by existing standards but are required to create their own standards. Both types of discretion apply to varying degrees in modern OHS legislation.

The provisions of early OHS legislation in Britain and Australia were detailed and prescriptive, allowing for little discretion on the part of duty-holders. The legislation clearly specified what must be done in order to comply. However, in 1972, a British committee of inquiry headed by Lord Robens recommended a reduction in the prescriptive detailed legislation. These recommendations were followed in 1974 when, in Britain, the Health and Safety at Work Act was enacted. Under the influence of Robens, prescriptive OHS Acts and Regulations were replaced by legislation containing “general duties” for those whose actions impact upon OHS, including employers, employees, and suppliers of industrial plant and materials. Australia followed the Robens model, with the introduction of Robens-inspired legislation in South Australia (1972), Tasmania (1977), Victoria (1981), New South Wales (1983), Western Australia (1987), Queensland (1989) and the Northern Territory (1986). General duties provisions now exist in the principal OHS Acts of all Australian states and territories. Most recently, in some Australian jurisdictions, general duties for construction designers have been added to the OHS legislation. The
“general duties” legislation differs from the prescriptive early legislation in that it does not clearly spell out the methods by which legislative compliance is to be achieved. Thus, the general duties require interpretation, judgment and discretionary decision-making.

Moreover, the general duties are not absolute, being qualified by vague terms like “so far as is reasonably practicable.” For example, section 28 of the Victorian Occupational Health and Safety Act (2004) requires that:

A person who designs a building or structure or part of a building or structure who knows, or ought reasonably to know, that the building or structure or the part of the building or structure is to be used as a workplace must ensure, so far as is reasonably practicable, that it is designed to be safe and without risks to the health of persons using it as a workplace for a purpose for which it was designed.

The standard for construction designers’ OHS duty is therefore “what would a reasonable designer have done in the situation?” It is reasonable to expect that as the risk to health and safety increases, the degree of effort exerted in controlling the risk should also increase. Thus, in order to ascertain what is reasonable in a given situation a design risk assessment is necessary.

Risk management

The risk-management process is similarly characterised by professional judgment and discretionary decision-making. AS/NZS 4360:2004 sets out the steps in the risk-management process. These steps (depicted in Figure 26.1) involve analysing the context in which the risk arises, identifying, analysing and evaluating risks and deciding how to treat risks. Risk assessment includes the identification, analysis and evaluation stages in the risk-management process (Standards Australia 2004).

Figure 26.1: The Risk-Management Process

![Risk Management Process Diagram]

(Source: Adapted from Standards Australia 2004)

Risk is understood to be a function of likelihood and consequence of an undesirable event, such as a work-related incident. In most instances, reliable quantitative risk data are not available to undertake objective, probabilistic assessments of OHS risks. OHS risk assessments are usually qualitative and characterised by considerable subjectivity. Consequently, the value of a risk assessment is limited by the knowledge and experience of the risk assessment team. Decisions about risk tolerance and appropriate means for risk reduction are also inherently subjective (Pidgeon et al. 1993). Where risks are deemed to be unacceptably high, decisions must be made about how to treat or control these risks. In the case of the most serious risks, a decision-maker might decide not to proceed with an activity, for example eliminating a hazardous design element from a design. An example would be the decision made to stop using asbestos sheeting for the construction of buildings once the risks posed by the material became apparent. However, in the case of most OHS risks, steps can be taken to reduce the level of risk. Risk-reduction measures are selected according to an established “hierarchy” of risk-control measures, which holds that it is better to eliminate a risk or “design out” a risk than to control it using measures that are reliant on safety procedures, training, or the use of personal protective equipment. An example hierarchy for the risk of falling from height is provided in Table 26.1.
Table 26.1: Example Risk Control Hierarchy for the Risk of Falling From Height

<table>
<thead>
<tr>
<th>Risk control category</th>
<th>Control measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eliminate the hazard</td>
<td>Structures should be constructed at ground level and lifted into position by crane (e.g. prefabrication of roofs or sections of roofs).</td>
</tr>
<tr>
<td>Substitute the hazard</td>
<td>▪ Non-fragile roofing materials should be selected.</td>
</tr>
<tr>
<td></td>
<td>▪ Fragile roofing material (and skylights) should be strengthened by increasing their thickness or changing their composition.</td>
</tr>
<tr>
<td>Isolate the process</td>
<td>▪ Permanent walkways, platforms and travelling gantries should be provided across fragile roofs.</td>
</tr>
<tr>
<td></td>
<td>▪ Permanent edge protection (like guard rails or parapet walls) should be installed on flat roofs.</td>
</tr>
<tr>
<td></td>
<td>▪ Fixed rails should be provided on maintenance walkways.</td>
</tr>
<tr>
<td></td>
<td>▪ Stairways and floors should be erected early in the construction process so that safe access to heights is provided.</td>
</tr>
<tr>
<td>Engineering controls</td>
<td>▪ Railings and/or screens guarding openings in roofs should be installed before roofing work commences.</td>
</tr>
<tr>
<td></td>
<td>▪ Temporary edge protection should be provided for high roofs.</td>
</tr>
<tr>
<td></td>
<td>▪ Guard rails and toe-boards should be installed on all open sides and ends of platforms.</td>
</tr>
<tr>
<td></td>
<td>▪ Fixed covers, catch platforms and safety nets should be provided.</td>
</tr>
<tr>
<td></td>
<td>▪ Safety mesh should be installed under skylights.</td>
</tr>
<tr>
<td>Safe working procedures</td>
<td>▪ Only scaffolding that conforms to standards should be used.</td>
</tr>
<tr>
<td></td>
<td>▪ Employers should provide equipment appropriate to the risk, like elevated work platforms, scaffolds, ladders of the right strength and height, and</td>
</tr>
<tr>
<td></td>
<td>ensure that inappropriate or faulty equipment is not used.</td>
</tr>
<tr>
<td></td>
<td>▪ Access equipment should be recorded in a register, marked clearly for identification, inspected regularly and maintained as necessary.</td>
</tr>
<tr>
<td></td>
<td>▪ Access and fall protection equipment such as scaffolds, safety nets, mesh etc. should be erected and installed by trained and competent workers.</td>
</tr>
<tr>
<td></td>
<td>▪ Working in high wind or rainy conditions should be avoided.</td>
</tr>
<tr>
<td></td>
<td>▪ Employers should ensure regular inspections and maintenance of scaffolding and other access equipment, like ladders and aerial lifts.</td>
</tr>
<tr>
<td></td>
<td>▪ Employers should ensure that scheduled and unscheduled safety inspections take place and enforce the use of safe work procedures.</td>
</tr>
<tr>
<td></td>
<td>▪ Employees should be adequately supervised. New employees should be particularly closely supervised.</td>
</tr>
<tr>
<td></td>
<td>▪ Employees should be provided with information about the risks involved in their work.</td>
</tr>
<tr>
<td></td>
<td>▪ Employers should develop, implement and enforce a comprehensive falls safety program and provide training targeting fall hazards.</td>
</tr>
<tr>
<td></td>
<td>▪ Warning signs should be provided on fragile roofs.</td>
</tr>
<tr>
<td></td>
<td>▪ Ladders should be placed and anchored correctly.</td>
</tr>
<tr>
<td>Personal protective equipment</td>
<td>▪ Employees exposed to a fall hazard, who are not provided with safe means of access, should be provided with appropriate fall-arrest equipment</td>
</tr>
<tr>
<td></td>
<td>such as parachute harnesses, lanyards, static lines, inertia reels or rope-grab devices.</td>
</tr>
<tr>
<td></td>
<td>▪ Fall arrest systems should be appropriately designed by a competent person.</td>
</tr>
<tr>
<td></td>
<td>▪ Employees should be trained in the correct use and inspection of PPE provided to them.</td>
</tr>
<tr>
<td></td>
<td>▪ Employees should be provided with suitable footwear (rubber soled), comfortable clothing and eye protection (for example, sunglasses to reduce glare).</td>
</tr>
</tbody>
</table>

(Source: Adapted from Lingard and Rowlinson 2005)
Alternative modelling approaches

The primary innovation in the development of the Australian design OHS decision support prototype is the use of “argumentation theory” in the representation of knowledge. In contrast to the rule-based approach adopted by Davison (2003) in the UK, design OHS knowledge will be captured and represented as a series of “argument trees”. An example design OHS argument tree is presented in Figure 26.2. The use of argument trees to represent expert knowledge was pioneered in a model of reasoning developed by Yearwood and Stranieri (2005) and has been successfully used to structure and represent knowledge in various fields of legal reasoning, including family law, refugee law and eligibility for legal aid.

In the case of the design OHS prototype, each argument tree will represent a hierarchy of factors relevant to the determination of a design-related OHS risk. The “root” of each tree will be the OHS risk rating associated with a particular design element and/or activity. The risk rating will be inferred with knowledge of two factors: the likelihood that an injury or illness will occur; and the likely severity of the consequence of that injury or illness should it occur.

For example, the distance of fall and the availability of anchorage points for fall-arrest devices are likely to be relevant factors that lead to an inference describing the consequence of a fall (i.e. the severity of the injury). The availability of anchorage points is conceptually related to the consequence rather than the likelihood of a fall because, in OHS theory, fall-arrest equipment will not prevent a fall from occurring but will limit the consequence of a fall if one does occur. The frequency with which workers must go on the roof to perform maintenance, the number of skylights, the strength of the skylight material, the roof pitch and protection for roof maintenance might be used to infer the likelihood that a fall will occur during maintenance work. Throughout the argument trees, a linguistic variable value on a “parent” node will be inferred from values on “children” nodes with the use of predetermined and appropriate inference procedures. For example, the risk rating is inferred using a multiplicative function for numeric variables derived from the values for the children “likelihood” and “consequence” nodes.

Argument trees are somewhat similar to fault trees and event trees that have been traditionally used to represent the interaction of events that have already contributed to safety incidents or which could lead to adverse safety outcomes in the future. However, argument trees differ to the extent that they do not begin with a specific incident (fault tree) or map the pathways from an initiating event to an identified outcome (event tree). Instead, argument trees are a particular type of logic diagram representing the relevant factors that an expert would consider in making an assessment or judgment about something, in this case in assessing an OHS risk. By specifying “values” for each node in the tree, a risk rating can be inferred, using the same logic and reasoning that an expert would use.

In argumentation-based KBSs, different inference mechanisms can be used according to the nature of knowledge being modelled. For example, in the “Split up” system (described in Stranieri et al. 1999), neural networks trained on data drawn from divorce property judgments were used to infer about half of the 35 nodes. In a different system, known as “Embrace,” which supported the determination of someone’s refugee status, inferences were always left to the discretion of the decision-maker (Yearwood & Stranieri 1999). In another system called “GetAid”, Stranieri et al. (2001) assigned weights to each linguistic variable and then summed these weights before comparing the result with a predetermined threshold to infer eligibility for legal aid. The mechanisms to be used to infer values on the “parent” nodes from values on the “children” nodes in the design OHS prototype have yet to be determined, but it is likely that several different types of inference mechanism will be used.

The representation of design OHS knowledge in this way is highly innovative and much better able to model the subjective and discretionary nature of OHS risk management than the rule-based approaches deployed in other OHS knowledge-based decision-support tools.

Argument trees represent a template for reasoning in complex situations. Thus, in a discussion about the level of risk posed by a particular design decision, two designers might disagree at the root node level. For example, one designer may perceive the risk to be high while another perceives it to be moderate. This difference in perception may derive from the different values assigned by each designer to subordinate nodes in the argument tree. For example, one designer may believe that the protection provided for roof maintenance is adequate, whereas another may not. However, although the two designers disagree, they can both accept the argument tree structure as a valid template for the derivation of their subjective risk assessments.

Thus, argument trees are intended to capture a shared understanding of relevant factors in the determination of a value (in this case the level of OHS risk). Irrelevant factors are not included in an argument tree. Thus, the colour of the roofing material is not considered relevant by design OHS experts, so is not represented as a node in the tree. (Although one can imagine circumstances where colour is indeed relevant to OHS, such as in the specification of emergency or warning signage).

The search for suitable measures that will reduce the risk level at the root node of the argument tree can also be automatically elicited from the tree itself. For example, a possible solution could be found by changing leaf node values until the desired level of risk emerges at the root node. Changing the protection for roof
maintenance to “adequate”, decreasing the number of skylights or providing suitable anchorage points for fall-arrest devices may result in a level of risk that is acceptable (for example, low). If not, then changing the value for other leaf nodes may reduce risk to a predetermined tolerable level. It is worth noting that when knowledge is modelled in this way, the search space of all leaf node value combinations will provide a list of all possible risk-control solutions to each identified design OHS hazard.
Figure 26.2: Example “Argument Tree” for the Risk of Falling Through a Skylight while Undertaking Roof Maintenance

Note: The argument tree presented is an example used to illustrate a concept. It is not based upon validated data and should not be used to assess risk or select appropriate control measures.
The argument tree approach to knowledge representation provides a simple structure for the assimilation of OHS knowledge into the construction design process. The advantages of this structure include:

- The risk rating (e.g., extreme) is not "hard-coded" and attached to each rule, but the end value will be generated via validated inference procedures embedded within the tree itself.
- Possible solutions to high-risk issues are not hard-coded (and therefore restricted). Rather, a search procedure can generate and test solutions by changing leaf nodes (i.e., base facts) and invoking inference procedures up the tree to ultimately generate a lower-risk option.
- Many rules are replaced by a single tree, resulting in a system that is easier to use and maintain. For example, as construction technology advances and new design solutions to OHS risks become known, relevant concepts and values can be relatively easily added into the argument trees. Also, where applicable, rule sets may be embedded in an inference procedure within any level of the tree. However, the use of the tree also enables mechanisms for drawing inferences, other than rules, to be deployed. This enables the approach to integrate a variety of existing inference methods and more readily accommodate inference methods yet to be discovered.

CONCLUSIONS

This chapter describes the conceptual design of a decision-support tool to support construction design professionals in integrating OHS risk management into the design process. This is important because experience in the UK has shown that construction design professionals are ill-equipped to manage OHS risks arising from the design process. OHS is typically not taught to construction design professionals in tertiary institutions within Australia and, thus, Australian design professionals may similarly lack the OHS and risk-management knowledge, skills, and abilities they need to comply with their statutory OHS duties. The R&D project currently under way adopts an innovative approach to modelling knowledge that is better suited to situations of discretionary decision-making and professional judgment than the rule-based systems of the past. As such, the project promises to make user-friendly, expert OHS knowledge readily available to construction design professionals.

REFERENCES


