IMPROVING HEALTH AND SAFTY IN CONSTRUCTION: A KNOWLEDGE-BASED APPROACH

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Within the past decade, the application of the Construction (Design & Management) Regulations (CDM) and other relevant legislation by the Health & Safety Executive (HSE) has contributed to efforts to improve the health and safety culture of the construction industry. However, when compared to other industries, construction still has a relatively poor health and safety record. In order to change this depressing situation, several efforts are being made to reduce the number of deaths, injuries and ill health. Such efforts basically involve identifying the root causes of accidents, developing safety audit checklists and creating models of risk factors for accidents in construction operations amongst others. However, evidence suggests that the effectiveness of health and safety management would require recalling and integrating knowledge of different duty holders relating to design, construction, operation and maintenance. Currently, knowledge-based applications focus on various aspects of construction management. However, very little has been done to incorporate the application of knowledge-based systems in the multidisciplinary health and safety management to date. Outlining the current knowledge-based systems and cases of using these tools in other construction domains provides sound evidence that knowledge-based systems can efficiently and effectively aid decision support. A case review of a knowledge-based system specific for designers for construction health and safety provides a concrete example of such an initiative. To improve upon these developments, a conceptual framework for identifying the knowledge chunks underpinning the application of The CDM Regulations in the entire supply chain was, therefore, conducted. Subsequently, the role knowledge-based systems can play in improving overall construction health and safety management was also investigated. Finally, suggestions for implementing further research are presented as a means of engendering wide debate.

Keywords: Knowledge-based system; CDM Regulations; Construction health and safety

INTRODUCTION

The construction industry is statistically one of the most hazardous occupations in the UK. It also ranks low in safety performance among the industrialized countries of the world (Kartam 1997). In accordance with the statistics from HSE, construction workers are six times more likely to be killed at work than other workers (HSE 2000). Within recent decades, the industry has made a lot of efforts in legislation concerning

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health and safety matters in order to reduce the number of illness, injuries and fatalities as a result of construction. There are two sets of construction-specific regulations, namely The Construction (Design and Management) Regulations 1994 (CDM) and Construction (Health, safety and welfare) Regulations 1996 (Holt 2001). The CDM Regulations became effective on the 31st March 1995 for the implementation of the design and management parts of the European Council Temporary or Mobile Construction Site Directive 92/57/EEC (Baxendale & Jones 2000). The aim of the CDM Regulations is to reduce the incidence of accidents and occupational ill-health arising from construction work by introducing procedures to improve the planning and management of health and safety on construction projects of all types, throughout every phase and involving all duty holders in the management of risk (Construction Confederation 2000). After nearly 10 years of implementing the CDM Regulations, the construction industry has achieved a large amount improvement in health and safety. However in 2002/2003, construction works still caused 71 worker deaths. This figure accounted for 31% of all fatal injuries to workers in UK. Meanwhile, 4098 workers incurred injury on the construction site and 8657 suffered different kinds of occupational illness (HSE 2003). A lot of previous research have paid a large amount of attention on analyzing data from accident reporting schemes, such as RIDDOR identifying causes of accidents and examining behaviour modification approach to improving construction safety (HSE 2003). Other research have also revealed that there are difficulties in applying CDM such as imprecise wording in relation to legal duties, meaningless paper work for key documentations and unawareness of safety and health problems in designing and constructing (Bennett 2004). Modifying regulations can solve some legislation problems, but others need a tool to maximize the effectiveness of undertaking health and safety responsibilities by duty holders.

A knowledge-based system (KBS) utilises certain artificial intelligent techniques collecting relevant knowledge and emulating the decision-making ability of a human expert to solve problems that are difficult enough to require significant human expertise for their solution (Giarratano and Rilley 2005). It is therefore envisioned that establishing a health and safety oriented KBS is an effective method to take advantage of former experience, expertise and rule of thumb to set precautions and take measures for eliminating and mitigating health and safety hazards, because almost all of the deaths and injuries that occur are foreseeable and preventable (HSE 2000).

An attempt is hereby made to analyse knowledge requirements by different duty holders according to the CDM Regulations. It also examines the possibility of using a KBS to assist these stakeholders improving construction health and safety decision-making and problem-solving. In addition, a KBS prototype made specially for designers is extensively reviewed to show the initiatives. Finally, several issues for the development of a multidisciplinary KBS for construction health and safety is emphasized to create a basis for further research.

THE CDM REGULATIONS: KNOWLEDGE REFINEMENTS

The CDM Regulations employ five construction phases to assign different health and safety commitments to Client, Planning Supervisor, Designer, Principal Contractor and Contractor. Such commitments include collecting and transferring relevant information, organising and coordinating interwoven works and compiling corresponding paper works.

Table 1: Summary of responsibilities for duty-holders in different construction stages (Construction Confederation 2000)

	Concept& Feasibility Stage	**Design& Planning Stage**	**Tender& Selection Stage**	**Construction Stage**	**Commission & Handover Stage**
Client	Structure contract to allow other duty-holders to carry out their duties	Continue to provide H&S information for plan	Ensure pre-tender plan accompanies tender documentation	Ensure sufficient time for PC to develop construction H&S plan	Receive H&S file
	Appoint D after assessing competence& resources	Consider competence& resources of PC	Has PS produced a suitable pre-tender health and safety plan?	Once construction H&S plan is sufficiently developed allow work to begin	Provide H&S file to any maintenance and construction workers
	Appoint PS after assessing competence& resources		Discuss competence& Resources of proposed PC and C		Update H&S file with any changes
	Begin gathering H&S information about premises, land, environment				
	Consider format required for the H&S file				
Planning Supervisor	Notify project to the HSE (F10)	Collate information from Client	Provide pre-tender H&S plan with tender documentation	Provide updated information as necessary	Hand H&S file to Client
	Discuss H&S information required from client	Collate design information on remaining hazards from D	If requested advise Client in selecting PC	Compile H&S file	
	Propose timetable for plan &file	Compile pre-tender health and safety plan	Collect information for H&S file	If requested provide advice to PC on competence& resources of D's and C's	
	Discuss content and format of H&S file	Ensure D is complying with duties			
	If requested advise Client on competence& resources of D, PC and C's				
Designer	Inform Client of CDM and their duties	Assess H&S during design	Assess H&S during deign	Provide updated design information as necessary	
	Begin assessing H&S aspects of design work	Reduce hazards where possible	Continue to provide information where necessary	Liaise with other D	
	Gather information regarding H&S	Liaise with PS and PC to provide information on risks	Provide information for H&S file	Provide information to PS for H&S file	
		Liaise with other D	Liaise with other D		
Principal	If involved at this stage begin	If involved at this stage in design	Respond to pre-tender plan	Develop Construction H&S	

Contractor	discussing H&S issues with all duty-holders	work:		plan	
		Assess H&S during design	Allocate adequate resources for H&S	Provide information to C	
		Reduce hazards where possible	Consider competence& resources of any contractors	Manage H&S on site	
		Liaise with PS on information to be provided on risks	Request further info if necessary to compile H&S plan	Provide induction and site specific training	
				Provide information to PS for H&S file	
				Liaise with PS regarding design changes	
Contractor	If involved at this stage begin discussing H&S issues with all duty-holders	If involved at this stage in design work:	Respond to pre-tender plan	Comply with PC and H&S plan	
		Assess H&S during design	Consider competence& resources of any Contractor	Provide information to PC for H&S file	
		Reduce hazards where possible	Provide information to PC if requested	Ensure all employees receive induction training	
		Liaise with PS on information to be provided on risks		Liaison with PC&PS regarding design changes	

Table 1 outlines the responsibilities that should be discharged by five duty-holders in different construction stages. Practically, however there are significant problems with the quality, quantity and effectiveness of communications and information exchanged amongst and between duty-holders (HSE 2005). In a new HSE report that aimed to provide guidance and recommendations for good practice to duty-holders, evidences were clearly shown that duty-holders needed more knowledge and awareness of their H&S responsibilities. The report also highlighted that more knowledge and experience of construction processes and H&S issues were vital for appropriate design and general risk assessments and method statements to be produced, understood and effectively implemented (HSE 2005). Therefore, three knowledge chunks are required to help duty-holders conduct health and safety management. They are:

- Knowledge of regulations: This kind of knowledge includes the awareness of relevant provisions, duties and the requirements on compiling documentations (pre-tender health and safety plan, hazards and risks assessment, health and safety plan and health and safety file). For example client needs to know which project information should be collected to support other duty holders;
- Knowledge of relevant construction techniques: It is a common sense judgment that the selection of correct construction techniques, methods and equipment are the prerequisite of health and safety; and
- Knowledge of project management: Duty holders should take other considerations (cost, programme, durability environment and etc.) into account when they solve

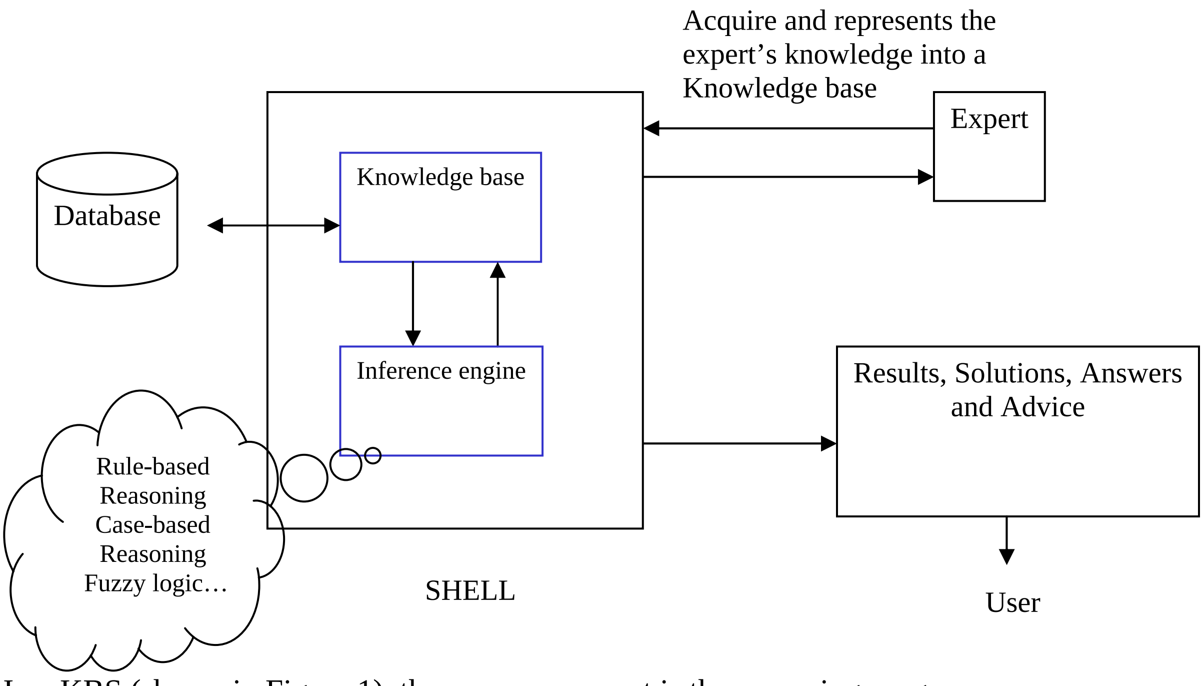
health and safety problems, because it is not usually feasible to avoid all risks at all cost.

It is quite difficult for duty-holders to capture such large amount of knowledge in reality. Although experts could be employed to solve relevant problems, such expertise is not available at most time. For instances, the experts may be simply too busy to answer all the queries, or on the other hand, time restrictions may affect the supply of the best expertise (Kingston 2004). However, a specific KBS may solve such intractable problems.

KNOWLEDGE-BASED SYSTEM (KBS)

Human knowledge is a fluid mix of framed experience, value, contextual information, and expert insight that provides a framework for evaluating and incorporating new experiences and information (Davenport & Prusak 1998). The attribute of human knowledge is perishable, inconsistent, difficult to transfer and expensive (Darlington 2000). Therefore, people utilize sophisticated computer techniques to develop a KBS, a kind of computer-aided programme that can applies human knowledge in a specific area of expertise to create solution. The working principle of a KBS is that it uses rules of thumb (heuristics) and symbolic logic to mimic the thought processes of the human expert (Awad 1996). Such programmes can help people make decision or provide advice to solve similar problems. KBS can bring about a large number of benefits. These included increased availability, reduced cost, reduced danger, permanence, multiple expertise, increased reliability, explanation, fast response, steady, unemotional and complete response at all times, intelligent tutor, and intelligent database (Giarratano and Riley 2005).

Figure 1: Working process of KBS (Source Awad 1996)



In a KBS (shown in Figure 1), the core component is the reasoning programme (inference engine) that is a logical process to draw reasonable inferences or conclusions form known or assumed facts (Awad 1996). Since there are different types of knowledge in terms of cognition characteristics, different reasoning techniques are designed to deal with them.

Rule-based Reasoning

The basic method making of judgments on certain matters is through the use of IF…THEN rules. When the premises (IF) are satisfied, the action (THEN) will be fired consequently. The rule-based reasoning uses a large number of interconnected and nested IF-THEN statements or rules to draw informative conclusions. If the knowledge belongs to procedural knowledge or declarative knowledge, including procedures, regulations or heuristics in the form of condition-action statements (IF…THEN), a taxonomic hierarchy, or a set of alternatives which need to be searched through, rule-based reasoning is probably the most suitable technique for automating the task (Kingston 2004). In rule-based reasoning, there are two inference strategies appropriate for different aspects of problem solving. These are backward and forward chaining.

- Backward chaining: starts with the goal and then looks for all the relevant, supporting processes that lead to achieving the goal (Awad 1996). For example, if there is a serial of interconnecting rules (IF…THEN), in order to find the possible solution to the goal (the action of the final rule), the programme goes from the premise of a certain rule to the action of another rule, to the premise of that same rule, on to another action, until there is no other rule’s action that matches the premise of the last rule. Therefore, backward chaining is goal-driven.
- Forward chaining: starts inference from the known data to look for which conclusion can be drawn. Therefore, forward chaining rules are considered to be data-driven (*ibid*).

Sometimes, the two kinds of reasoning strategy can work together to form opportunistic reasoning. In construction health and safety management, a system might apply forward chain with the known data to identify all possible risks, and backward chain to select the best solution to all risks.

Case-based Reasoning

When people are making some decisions, it is natural to draw the conclusion by comparing the current situation with past experience. Since this is an efficient decision-making method, computer-aid programme is designed to emulate such process. This is called case-based reasoning (CBR), and it assists people solve certain problems (Awad 1996). CBR stores descriptions of past experiences of human specialists, represented as cases, in a database for later retrieval when the user encounters a new case with similar parameters (Laudon & Laudon 2002). Normally, the semantic knowledge or episodic knowledge is suitable for such reasoning process. The typical CBR process involves the following steps (Darlington 2000):

1. Record the details of the current problem
2. Match these details against the details of stored cases to find similar problem situations.
3. Select the stored cases most relevant to the current problem.
4. Adapt the stored solution to the current problem

5. Validate any new solution and store the details of the new case.

The crucial points for the success of CBR is to abstract effective parameters adapt to all cases and to build considerable large case database. CBR has been used in bid decision-making (Chua *et al* 2001) and dispute resolution process selection (Cheung *et al* 2004).

Uncertainty and Fuzzy Logic

In real-world situation, inexact knowledge is usually used to express vague or uncertain conditions. Therefore, it is important for reasoning process to recognize inexact knowledge, especially when a situation changes over time (Awad 1996). Uncertainty and fuzzy logic are two types of techniques used to deal with inexact or vague knowledge.

Uncertainty usually depends on mathematical or statistical methodology to solve problems. It adds certainty factor into the reasoning process expressing the "confidence" or "belief" of a condition or judgment. Uncertainty refers to a subjective quantification of an expert's judgment, which describes the credibility of the conclusion given only the evidence shown in the premise of the rule. In health and safety risk assessment, for example, it would be a useful tool for prioritizing hazards and risks.

Fuzzy logic, a computer-based technique emulating human common sense, is usually used in KBS as well. In reality, people are accustomed to using some vague words to describe situations, such as using hot, cool and cold to express the feeling of temperature. Since there are no clear boundaries among these imprecise concepts, it is difficult for computer to deal with them. However, fuzzy logic can create rules that use approximate or subjective values and incomplete or ambiguous data (Laudon & Laudon 2002). The fuzzy reasoning approach usually passes through several steps (Perera and Imriyas 2003):

- Identification of control variables
- Fuzzification of variables
- Building the rule-base and inference, and
- De-fuzzification.

In construction and civil engineering, fuzzy logic is a suitable technique for dealing with the out of control factors: site, labour, equipment, climate, unforeseen circumstances, time dependence situations, and regulations (*ibid*.).

A new trend in KBS development--Virtual Reality (VR)

Since the viscosity (the richness or thickness of the knowledge transferred) of semantic knowledge and episodic knowledge is high, such knowledge is not easily and quickly absorbed by the receiver only through reading of text. Sound or graphic sometimes plays an important role in enhancing the effectiveness and efficiency of transferring certain knowledge. As KBS become more common, their use is expected to be integrated not only with database and word processors, but with imaging systems (Award 1996). VR with the power functionality of multidimensional presentation of data and solutions facilitate the user experience the advice or solution displayed on the screen in a realistic environment via visualization and sensing (*ibid*). Such sensory

KBS integrates sounds, visuals and sensations into the decision-making process that is close to real-time scenario.

VR techniques have a promising perspective in construction including design; construction integration; and construction scheduling, or 4D-CAD (Whyte 2002). However, due to the complexity of VR techniques, the combination between VR and KBS still needs further research.

The KBS application in the construction industry

The fragmentation of the construction industry has been identified by Latham and Egan as the critical barrier to achieving efficient communication among project team cooperation (Mukherjee 2002). Supply chains and organizational relationships in the construction industry are highly dynamic and transient due to the temporary nature of construction projects, inhibiting a continuous chain of communication (*ibid*). Moreover, the construction industry is a knowledge-intensive industry involving various different disciplines. With the trend of aiming at reducing waste, improve reliability, increasing efficiency, improving the distribution of risk and generally increasing the overall performance of the industry (*ibid*), the KBS has been considered as the best tool to help the construction industry to realize innovation. A 1995 report 'Construction IT – Bridging the Gap' observes that an industry-wide knowledge base should be set up to allow systematic capture and distribution of knowledge around the industry (*ibid*). Egan also recommended creating a 'knowledge center' to provide access to information regarding good practices, innovations and project lessons (Egan 1998). Therefore, a large amount of research about KBS application has been conducted in the industry covering planning (Shaked and Abraham 1995), designing (Thomas 2003), cost controlling (Perera and Imriyas 2003), bidding decision making (Chua *et al.* 2001), site management (Thomas 2003) and construction contract (Cheung *et al.* 2004).

Having reviewed the literature, it is evident that only a few efforts have focused on the application of KBS in construction health and safety management to date. Levitt and Kartam (1990) described a computer-based system developed with a focus on the owner attempting to evaluate a contractor safety performance or a firm safety program. Also in 2003, Health and Safety Executive (HSE) developed a KBS prototype to deliver health and safety information to designers in the construction industry. This system proposes to assist designers when applying the CDM Regulations in health and safety management. A more detailed assessment of this HSE system is hereby provided.

CASE REVIEW: A KBS PROTOTYPE TO DELIVER HEALTH & SAFETY INFORMATION TO DESIGNERS

A prototype KBS has been developed by NNC Limited and funded by HSE in the light of the brief that 'the poor health and safety record can be improved by encouraging designers to give more consideration to health and safety issues during the design stage' (HSE 2003). The core objective of this KBS is to improve health and safety decision making by; automatically checking designs; alerting risks to designers; and providing information on how to reduce the risk or remove the hazard completely within a CAD tool. The process is based on the responsibilities of designers under the CDM Regulations. This case review focuses on analyzing the function and structure of this KBS as a means of illustrating the procedure of building a KBS. It also identifies its limitations thereby presenting key issues for further research.

Function Identification

Objectively, three main functions are satisfied in the system.

- Health and safety information should be incorporated with a computer aided design (CAD) tool or standalone in order to avoid further work load to designer and easy to use.
- The KBS should allow the designer flexibly to modify relevant health and safety information (adding attributes to building objects) according to different project requirements.
- This KBS should be able to carry out risk check automatically and alert designers any risks found, together with providing risk and hazard elimination and mitigation methods.

Knowledge Acquisition

After identifying the main functions, KBS developers need to decide what kind of information would be worthwhile and where to collect it. Through studying designers' behaviour regarding health and safety issues in their designs and their attitudes towards the CDM Regulations, three kinds of data and information are identified and required for the KBS.

- Textual health and safety information: The textual information needs to be integrated into CAD and designers can view the relevant health and safety data for a particular type of object.
- Health and safety rules: Rules are required for automatic risk checking and warning.
- Object properties: These data involve elements' health and safety functioning and operational characteristics such as fragility, lifting equipment or cleaning method of certain building element.

In order to efficiently gather the above data and information, the system requires that these data and information are structured at a lower level including: risk level, accident cause, building entities building entity properties, textual information and rules.

In developing this KBS, two major sources were utilised to acquire relevant data, information and knowledge:

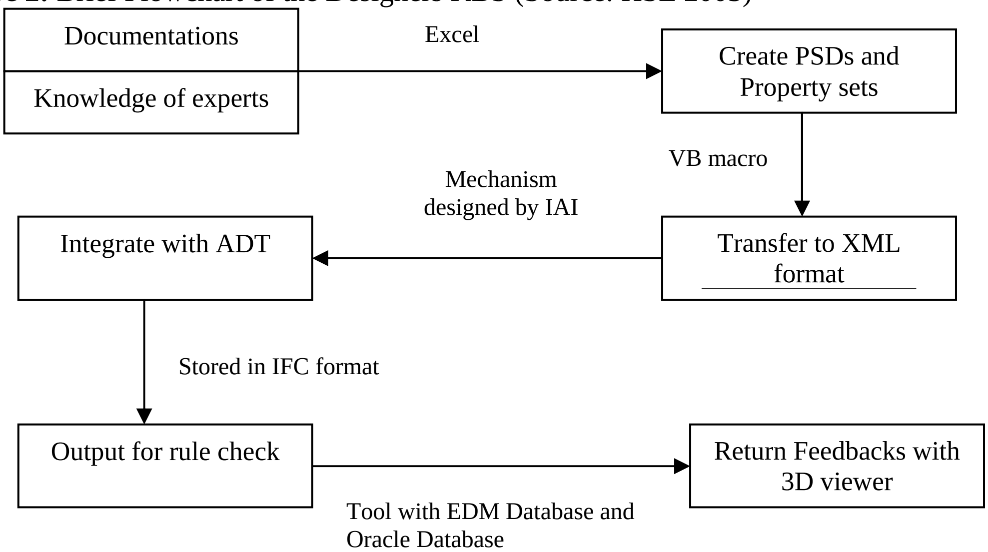
- Documentation: HSE documents, building regulations and standards and other relevant documents.
- Experts: A health and safety consultant was employed to assist in gathering data and feed relevant knowledge to the KBS. In addition, interviews with different designers also led to the acquisition of considerable knowledge based on their supervising experience on construction sites and also their planning supervisor experience.

Knowledge Representation and KBS tools

Figure 2 presents the architecture of this KBS

- Knowledge of relevant property's attributes is elicited into spreadsheets that are called Property Set Definition (PSD).
- PSDs is transferred into XML format by using VB macro, and then the XML format is integrated into CAD tools-AutoDesk Architectural Desktop (ADT) by a 'drag and drop' mechanism created by the IAI (International Alliance of Interoperability).
- Industry Foundation Classes (IFC) is used to share and exchange information between CAD applications.
- The rule checking process is implemented by EXPRESS Data Manager (EDM) Database and Oracle Database through a large web-based system. A 3D browser is also available for designer to interactively run the rule checking tool.

Figure 2: Brief Flowchart of the Designers KBS (Source: HSE 2003)



Advantages and limitations of the prototype KBS

The prototype KBS is state-of-the-art and enhanced with electronic 3D model checks. It can efficiently support designers' decision making on health and safety issues in certain construction domain. The main advantages are that:

- the combination of CAD tool with KBS provides a convenient means of implementing health and safety management in designing.
- hyperlink to relevant health and safety documents and websites in CAD application is useful. Having one location through which all health and safety information for designers can be accessed is a time-saver.
- the textual information in KBS is succinct and relevant.
- the 3D rule checking system can efficiently help designers identify risks and put forward effective solutions.

However, the KBS prototype also have following limitations:

- Capability of KBS: Being a prototype, the KBS only involves the information concerning the hazards of working at height and accidents due to falling and dropping of objects. Therefore, the suitability of the KBS for other health and safety issues depends on further development and investigation.

- Discipline: The KBS is specifically for building design rather than covering other disciplines such as civil engineering.
- Duty holders: The KBS focuses on the duties of designers, so it only provides limited help to other duty holders.

RECOMMENDATION FOR FURTHER RESEARCH

Considering the fact that health and safety issues involve multidisciplinary cooperation throughout the whole construction process, all duty holders' responsibilities should be taken into account in respect of building an effective KBS. Therefore, further research should focus on developing a 'hybrid' KBS that is supposed to comprehensively utilise suitable reasoning processes to enable different duty holders efficiently and effectively undertake their health and safety responsibilities under the CDM Regulations. In order to develop such a KBS, further research would focus on the following issues:

- Comprehensive Knowledge Framework Development: Identifying and establishing the knowledge framework concerning different duty holders' health and safety responsibilities is the guidance for the system development.
- Efficient Knowledge Acquisition: Acquiring necessary expertise, know-how and rule-of-thumb is the essence of the KBS.
- Suitable Knowledge Representation: Selecting reasonable knowledge reasoning process and adaptable KBS development environment is the pivot for building a practical KBS.
- Convenient Operation & Maintenance: User-friendly interface and ease of updating is important for the sustainability of the KBS.

CONCLUSION

Construction health and safety management is a complicated process that involves different parties, legal requirements, disciplinary professional knowledge and various external environmental considerations. However, it is also difficult for a project team to own all necessary knowledge. After introducing the relevant knowledge chunks for applying CDM Regulations and main functions of KBS, KBS is a powerful tool which provides a state-of-the-art approach to help the construction industry implement effective health and safety management. A case review also presented the feasibility of applying KBS in construction health and safety management; albeit in respect of designers. However, the recommendation for further research shows several key issues for the proposal of developing an effective CDM Regulation oriented KBS.

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