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IMPACT OF A MULTI-MEDIA DIGITAL TOOL ON IDENTIFYING CONSTRUCTION HAZARDS UNDER THE UK CONSTRUCTION DESIGN AND MANAGEMENT REGULATIONS

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SUMMARY: *Research has shown that up to half of construction accidents in the UK had a link with design. The UK's Construction, Design and Management Regulations, (CDM, 2015) place duties on designers of construction projects to consider the health and safety implications of their designs. However, the majority of designers fail to recognise the impact on health and safety that they can make. Previous work shows that visual methods have been used to develop shared mental models of construction safety and health hazards in construction and design teams. Potentially, these methods could also include links to alternative construction processes that may be utilized by designers to reduce the inherent hazards in the design, thereby enhancing their knowledge of construction and maintenance processes from the very people who are affected by the designs. The study reported in this paper aims to improve how designers involved in construction projects learn about how their design influences the management of occupational health and safety at the construction stage. The proposed approach involves the development of a multi-media digital tool for educating and assisting designers on typical design-related hazards. This prototype tool was used in an intervention study with novice and experienced designers, split evenly between experimental and control groups. These groups were assessed via a novel hazard test using fictitious Computer Aided Design (CAD) drawings. The results showed all experimental groups outperformed control groups, with the novice groups demonstrating the greatest increase in both hazards spotted and quality of alternative options recommended. Current research in this area promotes automated design systems for designers using Building Information Modelling (BIM). However, the research presented here advocates keeping the 'human' in control while supplementing designers' knowledge with tacit knowledge gained from interaction from the developed digital tool, so that they can make informed design decisions potentially leading to safer designs.*

KEYWORDS: *CDM, Design, Prevention through Design, Safety in Design*

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1. INTRODUCTION

Several research teams have investigated the relationship between design and construction accidents with Haslam et al. (2005) reporting that up to half of the accidents that they analysed had a connection to design. The UK's Construction (Design and Management) Regulations (CDM, 2015) place duties on designers of construction projects to (amongst other things) consider the health and safety implications of their designs in relation to the construction, use and maintenance (including cleaning) of the assets produced. However, the majority of designers fail to recognise the impact on health and safety that their designs can make (Haslam et al., 2005). Several reasons have been attributed to this which includes lack of resources and time, cost, client requirements and a lack of tacit knowledge gained through experience (Haslam et al., 2005; Behm, 2005). This last factor was explored by Hayne et al. (2015) who showed a link between site experience and the designer's ability to identify and mitigate construction hazards in designs.

Unfortunately, designers in the UK construction industry are increasingly educated and trained with little or no site experience (Hayne et al., 2015). Specifically, the main professional institutions have been gradually withdrawing the requirement for architects and engineers to spend prolonged periods of time on construction sites. The situation is compounded by the increased academic requirement of a Master's degree in order to become chartered by the conventional route and the tendency of universities to produce "engineering scientists" (Hayne et al., 2015). Designers are increasingly working exclusively within the design office environment. They are immersed in the use of digital technologies, working in isolation, and not challenging the outputs of computer software commonly used in their daily routine. Essentially, they are becoming over-reliant on computer-generated information (MacLeod, 2016). This often implies and leads to a lack of appreciation and understanding of key fundamental concepts in any domain which erodes their skills, knowledge and experience of imperatives critical to health and safety (Hayne et al., 2015). It is, therefore, important that the details of potential hazards are communicated to designers in a way that will aid their development and training, augmenting the site experience they have (if any). One of the ways this can be achieved is by the use of links to visual aids demonstrating the construction and maintenance processes complete with experiences of construction operatives, foremen and facilities managers etc. to explain the actual details of the hazards. These linked aids could act as an *aide-memoir* to the designers while considering the OSH aspects of their designs.

The study reported in this paper aims to improve how designers involved in construction projects learn about how their design influences the management of occupational health and safety at the construction stage. Previous work shows that visual aids have been used to develop shared mental models of construction safety and health hazards in construction and design teams (Hare et al., 2013; Lingard et al., 2015; Zhang et al., 2015). However, this could be augmented by linking these aids to alternative construction processes that may be utilised by the designer to reduce the inherent hazards in the design, thereby enhancing their knowledge of construction and maintenance processes from the very people who are affected by the designs. Current research in this area promotes automated design choices for designers via Building Information Modelling (BIM) (Liu and Issa, 2014; Zhang et al., 2013). However, the research presented here advocates keeping the 'human' in control whilst supplementing designers' knowledge with experiential knowledge so that they can make informed design decisions.

1.1 Design for Occupational Safety and Health (DfOSH)

There have been a number of studies undertaken in recent years, using terms such as 'Design for Safety' (DfS), 'Prevention through Design' (PtD), 'Safety in Design' (SiD) and 'Design for Health' (D4H). These terms seem to be used interchangeably and can be collectively referred to as 'Design for Occupational Safety and Health' (DfOSH). Therefore, this is the term adopted for the study reported here, even though these other terms may have been used by the authors cited.

Trethewy and Atkinson (2003) define the principle of DfOSH as "Improved safety, health and environment outcomes through better design…". In order for this process to be effective, hazards need to be identified during the design process and where possible eliminated or minimised (Behm, 2005; Toole and Gambatese, 2008; Trethewy and Atkinson, 2003). It is acknowledged that accident causation is often complex and multi-facetted (Gibb et al., 2006; Martínez et al., 2010; Gambatese et al., 2008). However, research has been undertaken within the UK that shows that up to half the accidents have a link to design whilst that is often not the sole cause and other factors also contribute (Haslam et al., 2005). This figure is close to that noted in the European Union directive 92/57/EEC (Anon., n.d.) 13 years earlier and after the introduction of the CDM Regulations. The results of the research by Haslam et al. (2005) further suggest that little improvement had been made in the decade following the introduction of the Construction (Design and Management) Regulations (1994). It is important to recognise that this comment relates specifically to statistics and ignores the heightened awareness noted by Howarth et al.(2000). Considering such comments, it is reasonable to assume that many UK designers fail to appreciate the benefits of DfOSH. Researchers have found that many designers do not recognise the impact on OSH that they, as designers, can make (Haslam et al., 2005). Gambatese and Hinze (1999) undertook a study in the USA where they identified that designers are not aware of their impact on site safety and lack the knowledge and ability to modify their designs to improve safety. This view is also supported by the work carried out by Qi et al. (2011). It should be noted that unlike the UK, American designers do not have a legal, contractual or regulatory requirement to consider OSH within their designs (Behm, 2005).

Few UK designers embrace the principle of DfOSH despite the CDM regulations being in force (Haslam et al., 2005). Some of the reasons for this include lack of resources and time, cost, client requirements and a lack of tacit knowledge gained through experience (Haslam et al., 2005; Behm, 2005). Other research teams have also highlighted that designers are reliant upon tacit knowledge to adequately discharge their legal duties (Morrow et al., 2015; Gangolells et al., 2010; Hadikusumo and Rowlinson, 2004).

As design is a representation or simulation of the complete artefact it must be questioned how a designer undertakes the process of DfOSH. It has already been suggested that designers are reliant upon tacit knowledge, often developed from experience. It is well established that design is a cognitive activity that is subjective and relies heavily on experience and that it is classified as a hard problem lacking in structure thereby requiring often heuristics-based approaches not easily possible to be articulated to others (Simon, 1996; Lawson, 2005). The foundation of modern building engineering is a combination of craft knowledge, rules of thumb and the application of science (Blockley, 1981).

Design is a complex process involving many actors who input to a design that undergoes numerous iterations. Design decisions are seldom made independently by a single designer. It is also common that OSH hazards which are identified early in the design process are replaced by unidentified hazards as development of the design occurs (Lingard et al., 2012). Szymberski (1997) asserts that the ability to influence OSH on site diminishes with time throughout the entire project schedule as illustrated in Figure 1. It is apparent that the conceptual stage of a project offers the maximum opportunity to influence OSH. It is also evident that hazard identification should be repeated with subsequent iterations of the design to ensure new unidentified hazards are not adopted into the revised design.

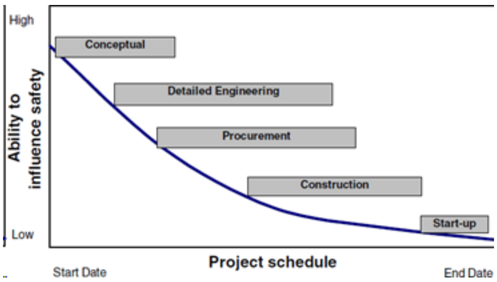

FIG 1: Time and Safety Influence curve (Szymberski, 1997)

The additional factor that is required to address this challenge is the ability to imagine, which Bronowski (1979) clearly links with vision. Bronowski goes on to suggest that humans are unique in that they can imagine and consider options which in the case of DfOSH would include construction processes previously witnessed, that would allow the adoption of least hazardous processes. Besides, foresight is also required when a design is reviewed which generally comes with experience giving foresight of the consequences of the design and the associated construction process that has been imagined. Again, Bronowski (1979) suggests that foresight is unique to the human but has been evident for millennia. He provides the example of the discovery of stones in Olduvai that were stockpiled for use as stone tools. Ancient man had the experience that his stone tools would break and need replacing, hence he would collect suitable stones for later use. Subsequent research has identified that other animals such as primates possess the ability to imagine (Suddendorf, 2006) but this does not detract for the need for imagination when undertaking DfOSH. Designers need foresight to anticipate what may occur when operators are constructing and maintaining their designs. For example, foresight will tell a designer that mechanical plant on the roof will need servicing and a safe access route to the plant will be required that will not put the maintenance staff at risk. This is a trivial example that most designers would hopefully be aware of but a more complex hazard could be that a specific part of the plant will need replacing. The designer ought to have considered whether the design allowed for a crane of suitable size to be located close to the plant or does the landscaping, with its planting and water features, prevent the use of a crane? If the designer has not been exposed to the latter situation their experiences will not give them the foresight to anticipate these situations arising in the future.

The HSE have produced 'Red, Amber, Green lists' (RAG lists) that are described as practical aids for designers, highlighting what to avoid and what should be encouraged (CITB, 2015). The guides are often referred to during training sessions on CDM and designing for OSH as they are brief and simple to use. Curiously, the majority of the recommendations relate to the detailed design stage of a project when the opportunity to achieve maximum impact has already passed. This could provide assistance to inexperienced designers who may not consider DfOSH during the design, but may not be as useful for earlier stages (Morrow 2015). Inexperienced designers may also use the RAG lists as a check-list without actually looking for additional hazards (Hayne, 2016).

More recently, the working group on BIM4H&S set up by the UK BIM task Group has focused mainly on developing guidance and case studies, the most notable of which was the publication of a Publicly Available Specification (PAS) for managing OSH information in a BIM environment: PAS 1192-6 (2018) *Specification for collaborative sharing and use of structured Health and Safety information using BIM* (BSi, 2018). The PAS provides guidance on how OSH information is produced and flows through the lifecycle of construction assets. The PAS requires "the contextualization and filtering of hazards and risks to prioritize the elevated risks and aspects that are safety critical" (PAS 1192-6), and is structured around the PAS 1192 process framework (Figure 2).

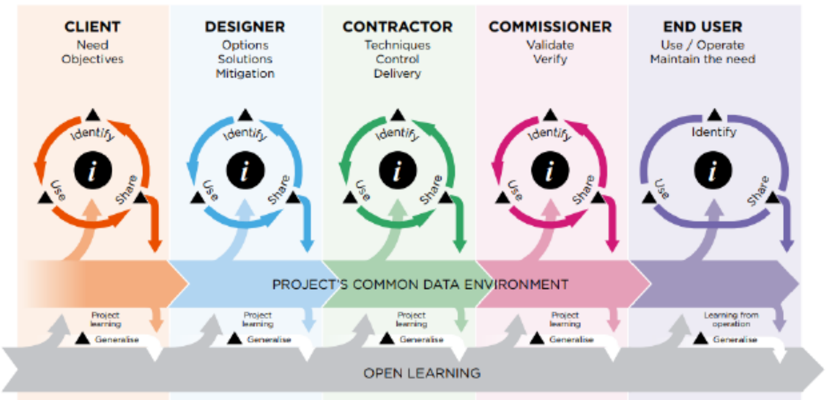

FIG 2: Progressive Development of H and S Information (Source: PAS 1192-6 2018)

A key element of the PAS 1192-6 process is the 'Identify-Share-Use' cycle as illustrated in Figure 2. It would make sense for digital tools in this area of development to align with BIM in general and with PAS 1192-6 in particular. This includes the development of digital libraries to help identify OSH risks that can be shared in a 'common data environment', e.g. a software programme that all project members can use. Another important factor identified in the PAS is the need to attach relevant OSH risk information to one or more of the following 'attributes':

- Product;
- Activity;
- Location.

This acknowledges that 'products' (such as substances, materials, components and elements); 'activities' (such as working at height); and 'locations' (such as a confined crawl space) can all be associated with OSH risks. BIM technologies need to use a standard classification system in order to share and exchange information. A standard classification system that precribes unique codes for each class is Uniclass (59) which is the system widely used in the UK (and other) construction industry. The PAS also lists standard classifications that can help organise OSH risks into categories of harm. Together, these represent the most critical aspects to consider for developing any form of digital tool to assist with OSH if aligning with BIM and PAS 1192-6 (BSi., 2018).

However, for reasons explained later (figures 4-6), the PAS 1192-6 attributes had to be modified based on the pilot testing of the tool developed in this study.

Notwithstanding the above discussions pertaining to the impact that design decisions may have on the causation of accidents, it is important to remember that "It is incorrect to assume that simply by implementing the design for safety concept, construction site fatalities will automatically be eliminated" (Gambatese et al., 2008). Whilst many attempts have been made to develop digital tools to aid designers in this respect, including those embedded within BIM systems, the fundamental need for the designer to be competent is a common thread. The nature and scope of education for designers, combined with relevant site experience, has shown to be critical to successful DfOSH outcomes. Therefore, technology that seeks to remove the designer from the decision making process around DfOSH – such as automated design systems – could do more harm than good. A knowledge-based system seems to be the favoured method of giving designers the ability to make informed decisions on DfOSH. However, text-based systems have proven to be cumbersome (Hare et al., 2019). Whereas, visual (pictorial, multimedia) databases may be able to overcome the problems posed by overly textual and verbose systems and provide a more effective solution. It is acknowledged that designer knowledge is only one of many factors that can influence DfOSH and other factors like available budget, competing objectives, form of procurement, etc. may have just as important influence on accidents on sites. However, these are outside the scope of this paper.

2. RESEARCH METHODS

The overall process of conducting this study is shown in Figure 3 which is self-explanatory.

The method employed in this research was one of exploratory action research, combined with the use of an experimental design to evaluate the ability of a multimedia digital tool intervention on designers' OSH knowledge and practices. This was expected to improve how designers can influence specific hazards (relating to construction, use and maintenance of built assets). To achieve this, the following methods were employed.

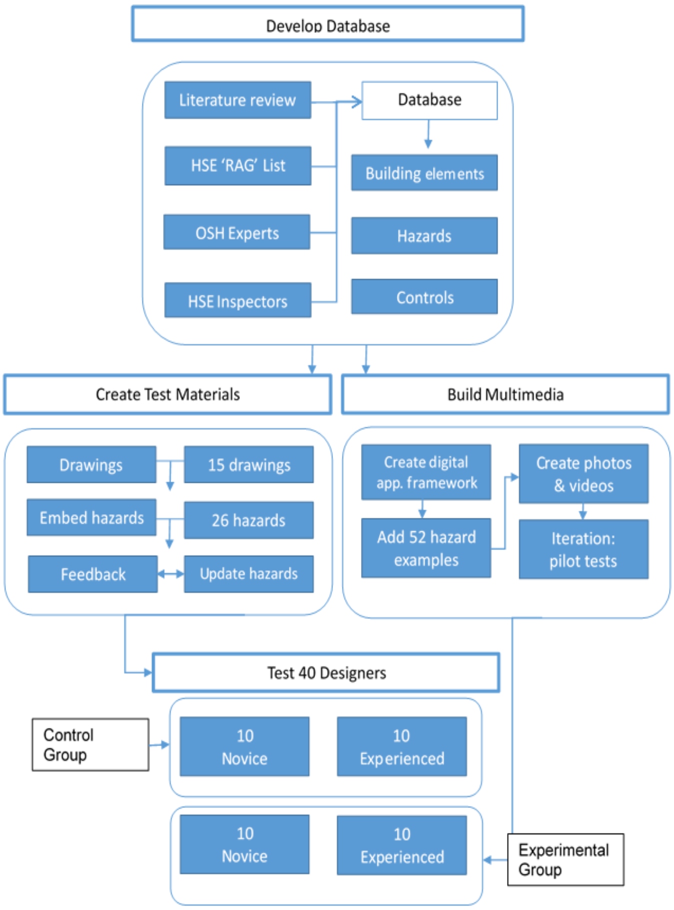

FIG 3: The overall research roadmap

Sector-specific hazards, which can be influenced by designers of buildings and structures, were identified through a systematic review of academic and industry literature. The literature search was supplemented by interviewing experienced Health and Safety Executive (HSE) Construction Division inspectors, construction OSH professionals and facilities managers. Other experienced professionals were recruited from the research team's industry network. This included Directors and Senior Managers.

The 'design influenced hazards' (those introduced as a result of the design or specification (see Figure 4) informed the design and development of a multi-media digital tool (Figure 4) and linked hazard test instruments in the form of digital drawings. Recently developed BIM PAS 1192-6 (BSi., 2018) for OSH information was used as the main reference point. A consequence of this was to specifically label designer-related hazards in relation to the three attributes of 'Product'; 'Activity'; and 'Location'. Therefore, each hazard in the database could be labelled in relation to one or more of these attributes, e.g.:

- Products: such as substances, materials, components and elements;
- Activities: such as working at height; and
- Locations: such as a confined crawl space.

Another critical step in classifying hazards in the database was to include the type(s) of injuries or harm resulting from each hazard. Again, the classifications in the BIM PAS 1192-6 (BSi., 2018) were utilised e.g. 'fall from ladder' 'electric shock' etc. The digital tool was developed iteratively, with pilot testing and refinement until it was deemed ready for the experiment. It should be pointed out that the PAS 1192 documents are gradually being superseded by the International Standards Organisation (ISO) standards on BIM as a series of ISO19650 documents. At the time of writing this paper only the first two part of PAS1192 documents have been published but the rest are due to be out soon. It is, however, expected that the main spirit and concepts of the PAS documents will still be preserved and are therefore still relevant.

A sample of 40 designers (based on the timeframe for the study), from two typical industry groups of architects and civil engineers (the target population being those traditionally identified as a designer under the UK CDM Regulations), were recruited for the next stage of the research. These were recruited via the network of designers who have attended CDM courses and the network of designers known to the research team. The sample was purposefully chosen using the following criteria; half (20) experienced (deemed as more than 5 years' experience, which must include site experience) and half (20) novice (less than two years post graduate) designers.

TABLE 1: Sample

		Expert	Novice	Total
Experimental Groups	**Architect**	5	5	10
	Civil Eng.	5	5	10
Control Groups	**Architect**	5	5	10
	Civil Eng.	5	5	10
		20	20	**40**

Designers were invited to engage with the developed materials in a carefully controlled experiment. The experiment evaluated the effects of the multimedia materials on decision-making and users' capability in designing for OSH in the construction industry. The experiment determined whether use of the multimedia materials improved users' ability to foresee OSH hazards in designs by measuring both the quantity of specific hazards identified and the quality of design outcomes (design controls) put forward.

The sample of 20 novice and 20 experienced design professionals were randomly assigned into multimedia user (experimental) and non-user (control) groups. Design problem scenarios were presented to participants in sessions in a controlled environment. Participants were asked to review the set of CAD drawings in these sessions, to identify hazards and make decisions about designing for OSH. An explanation was given to the participants of what was expected and they were given an opportunity to ask any questions. For the first part of the experiment, all participants were asked to use their own knowledge to identify hazards and alternative solutions. In the second part of the experiment, participants were split into two groups: those who used the tool to identify hazards and alternatives and those who used their own resources, for example: the HSE website. Participants were allowed to use the second half of the experiment to not only add new hazards and alternatives but to also edit their current ones if they wanted. The pre-intervention responses were written with a red pen and the post-intervention responses with a green pen to distinguish between the two (Hayne et al. 2017).

The average (mean) number of project-specific hazards identified per group was measured. Following the method used by Hayne et al (2015), generic hazards were ignored. Out of scope items included general references to e.g. work at height (if not related to a project-specific item); general good practice to comply with Building Control/Standards, such as fire protection; or those considered out of scope for not being OSH related. The hierarchy of controls score (from 5 down to 1) also followed the Hayne et al (2015) method:

(5) Eliminate (through design): prefabrication; locate item at ground level;

(4) Reduce (trough design): design in edge protection; substitution of lesser hazard;

(3) Reduce (engineering controls): local exhaust ventilation; temporary edge protection;

(2) Inform of administrative procedure: 'contractor to provide method statement'

(1) Control through PPE: 'contractor to provide PPE'

Data was compared for multimedia-user (experimental) and non-user (control) groups and also between novice and experienced designers. Collecting data before and after use of the multi-media tool enabled OSH knowledge, skills and abilities to be compared for both novice and experienced design professionals. Comparisons between experimental and control groups used the Mann-Whitney between group test. This tests for statistically significant differences to separate groups (experimental and control). Changes before and after interventions within the same groups used the Wilcoxon Signed-Ranks Test, commonly associated with 'within group' 'pre-post' tests.

2.1 Development of the database

In addition to these labels used for classifying the hazards as mentioned before, one of the features of BIM technology is its interoperability, achieved through the use of a common language or classification systems. Therefore, to increase the database's interoperability, the most common unified classification system for construction products, elements and locations was used for labelling, known as Uniclass (NBS, 2015).

Another critical step in classifying hazards in the database was to include the type(s) of injuries or harm resulting from each hazard. Again, the classifications in the new BIM PAS 1192-6 (BSi., 2018) were utilised, e.g. 'fall from ladder', 'electric shock' etc.

The final section of the database was the strategies for designers to address the hazards. This was classified in relation to a simplified version of the 'principles of prevention' (sometimes also described as 'hierarchy of controls') stipulated in the Management of Health and Safety at Work Regulations (1999), as developed by Hayne et al. (2017), namely elimination, substitution, civil engineering controls, administration controls and PPE. Higher-level controls (as mentioned earlier) are interpreted as evidence of greater knowledge and understanding of how designer decisions can improve the overall management of OSH. This also provided a method of evaluating strategies to address the designer-influenced hazards discussed later.

2.2 Hazard-test instruments

The hazards and corresponding designer actions allowed a series of hazard-test instruments to be developed, piloted and refined for each of two industry subgroups: commercial building (architects) and civil engineering. These instruments consisted of hazards embedded in 'design' solutions (CAD drawings), which knowledgeable designers can identify, following the method created by Hayne et al. (2017).

A total of 15 CAD drawings were developed, based on a fictitious office development and external works. The drawings were carefully constructed to include as many of the hazards as possible that were identified in the database, while maintaining a realistic appearance (see excerpts from drawings in Figure 4). This resulted in 26 hazards being incorporated into the drawings, covering e.g. specifications that lead to working in confined spaces, work at height and heavy lifting; locating elements such as manholes, lighting, single steps in hazardous positions; and ignoring stability of temporary works.

The drawings were accompanied by a feedback sheet to record the designers' responses. This included some demographic information (to confirm profession and level of experience) and essentially two columns: 'hazards' and 'alternatives'. This allowed comparison of designers' reasoning and responses in relation to OSH hazards in the designs. The test instrument also facilitated a method to evaluate them, i.e. determine if they are generic or specific; and high or low ‘hierarchy of control’ solutions.

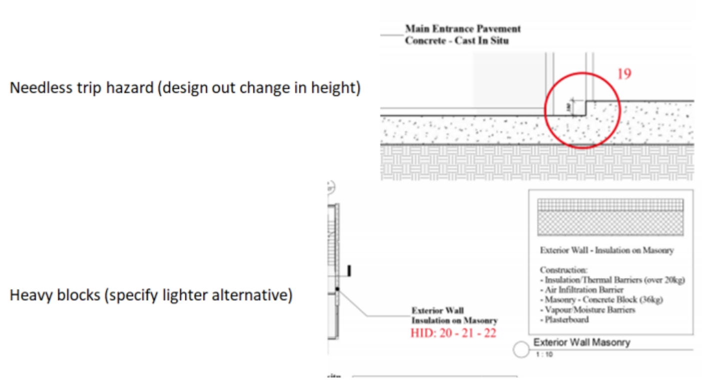

FIG 4: Excerpts from CAD drawings

2.3 Digital multimedia tool

The hazards and corresponding designer actions above also allowed a series of multimedia materials to be developed within a digital web-based tool. These included photographs and videos in which the constructors and end users of designs talk about and show how design decisions can impact OSH during construction, maintenance or subsequent operation of a facility.

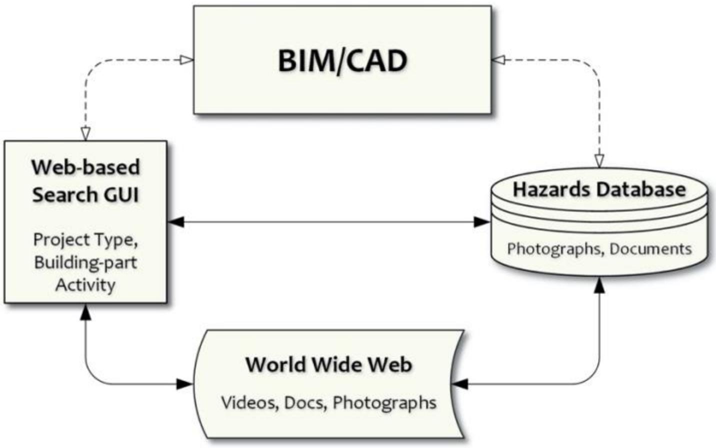

FIG 5: A schematic architecture of the tool

A schematic architecture of the tool is shown in figure 5. The hazards database can be searched using the different criteria discussed before from the homepage of the tool. There are different kinds of media-based examples of the hazards stored in the relational database including links to additional sources like videos etc. on the web. The dotted line to and from BIM/CAD box signifies a ‘loose’ link from the test drawings etc, with the tool database and the user interface meaning a direct link does not exist at the moment. However, it is envisaged that a proper link will enable the designer to jump into the tool directly from the CAD or BIM system being used by the designer and revert back to their designs after interacting with the database to seek advice etc. on the hazard in question.

The tool was developed iteratively, with pilot testing and refinement until it was deemed ready for the experiment. A critical change to the appearance of the tool was to hide the original Uniclass codes. The designers who participated in the pilots found the Uniclass codes confusing and complicated. Indeed, the main refinement that resulted from the pilots was to simplify the filter options in the tool to the three shown in Figures 6-8. However, the original PAS 1192-6 codes have been retained within the design of the tool, hidden from the user but available for future use with BIM systems, i.e. the three codes of ‘location’, ‘activity’ and ‘product’ are attached as attributes to each hazard.

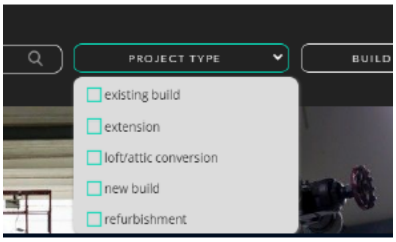

FIG 6: Filter 1 - Project Type

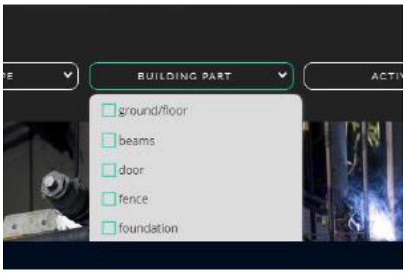

FIG 7: Filter 2 – Building Part

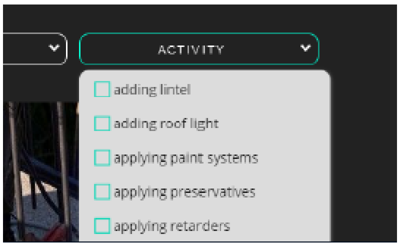

FIG 8: Filter 3 – Activity

The tool homepage lists each of the main hazards using photographs and a short description (Figure 9). Filtering provides a shorter list of specific hazards. Clicking on the photo leads to designer options, classified as 'eliminate', 'reduce' and 'inform' (Figure 10) in relation to the possible designer actions available to address the hazard (as opposed to contractor controls). These alternative options also include visual examples (photographs) and include links to external photos and video clips if further explanation is required.

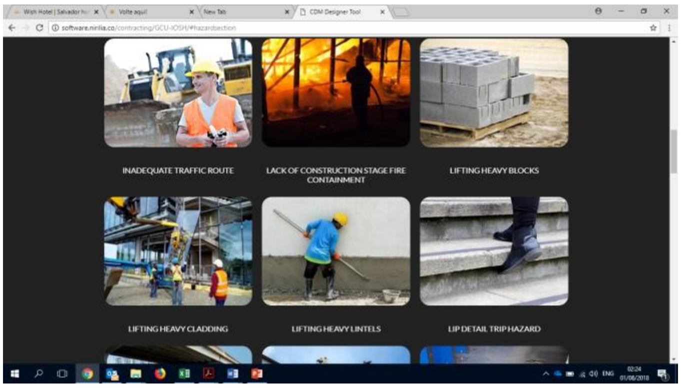

FIG 9: Screenshot of hazards on multimedia tool's homepage

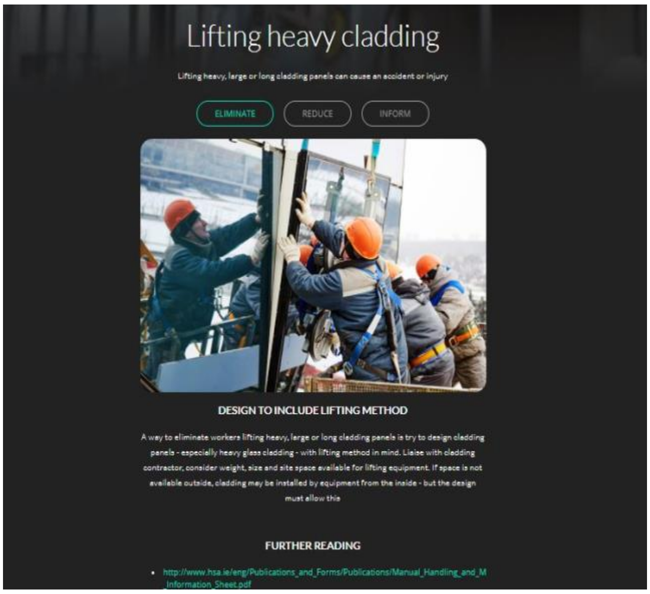

FIG 10: Screenshot of control measure (cladding hazard)

3. RESULTS AND DISCUSSION

Designers were invited to engage with the developed materials in a carefully controlled experiment in a university computer lab. Participants were randomly split into experimental and control groups and given access to a PC with internet access. They were then given a printed set of fictitious drawings incorporating intentional design hazards. Both groups were given 30 minutes to record as many hazards and designer actions (controls) as possible. The experimental group were then given access to the digital tool, whilst the control group were allowed to search the world wide web. Both groups were given a further 30 minutes to add to the list of hazards and controls. The experiment evaluated the effects of the multimedia materials on decision- making and users' capability in designing for OSH. The experiment determined whether use of the multimedia materials improved users' ability to foresee OSH hazards in designs by measuring both the quantity of specific hazards identified and the quality of design outcomes (design controls) recommended.

Data was compared for experimental and control groups and also between novice and experienced designers. It was also possible to compare between architects and civil engineers. The ability to identify 'generic' hazards is associated with a basic or superficial understanding of how design impacts on OSH, whereas being able to link specific hazards to particular design choices is seen as indicative of a more knowledgeable designer (Hayne et al., 2015). This informed the framework for structuring the data for analysis.

The two main units for analysis were:

- Number of project-specific hazards identified;
- 'Hierarchy of controls' score.

The average (mean) number of project-specific hazards identified per group was measured. Following the method used by Hayne et al. (2015), generic hazards were ignored.

The hierarchy of controls score also followed the method devised by Hayne et al. (2015) as shown in Section 2. This utilised a simple weighting depending on what alternative options were recommended by designers. In some cases, more than one alternative option was listed by designers. In these cases, the highest-ranked option in the response was used.

Three researchers reviewed the results to ensure reliability. An initial cross reference of the first five participant scores was performed to check inter-rater reliability. This was shown to be between 0.85 and 0.96 for the five participant scores (number of controls x weighting). The following examples were used to inform decisions around weightings:

‘Eliminate’ examples:

Specify precast piled foundations to avoid need for breaker on pile caps

Design in lifting points for the cladding to avoid manual handling

Reposition manhole away from road to avoid workers being run over

‘Reduce’ examples:

Specify lighter blocks for concrete blockwork wall

Include structural wire mesh over roof light

Position lighting at low level to reduce working height

‘Inform and control’ examples:

Discuss cladding options with cladding contractor to mitigate storage and handling risks

Liaise with structural engineer and contractor to discuss best location of tower crane

The resulting quantifiable data allowed visual graphical analysis to detect any rise in frequency of hazards identified or ‘hierarchy’ score among the participants. While the data is quantitative, it should not be analysed using parametric tests as it violates the required assumptions for such tests. It is more appropriate to check for statistically significant changes and differences using non-parametric tests as data of this nature is rarely normally distributed and the hierarchy scores in particular are not true scales.

The hazards identified by the experimental group (before and after) are shown in Figure 11. This constitutes a total of 339 hazards (234 before + additional 105 after) for this group. The greatest increases in hazards identified were: high level lighting (n. 9); flooring ‘Control of Substances Hazardous to Health’ (COSHH) (n. 8); paint COSHH (n. 8); welding steel frame (n. 8). The uplift in number of hazards identified by the experimental group amounts to 45% of the original number as a result of using the digital tool.

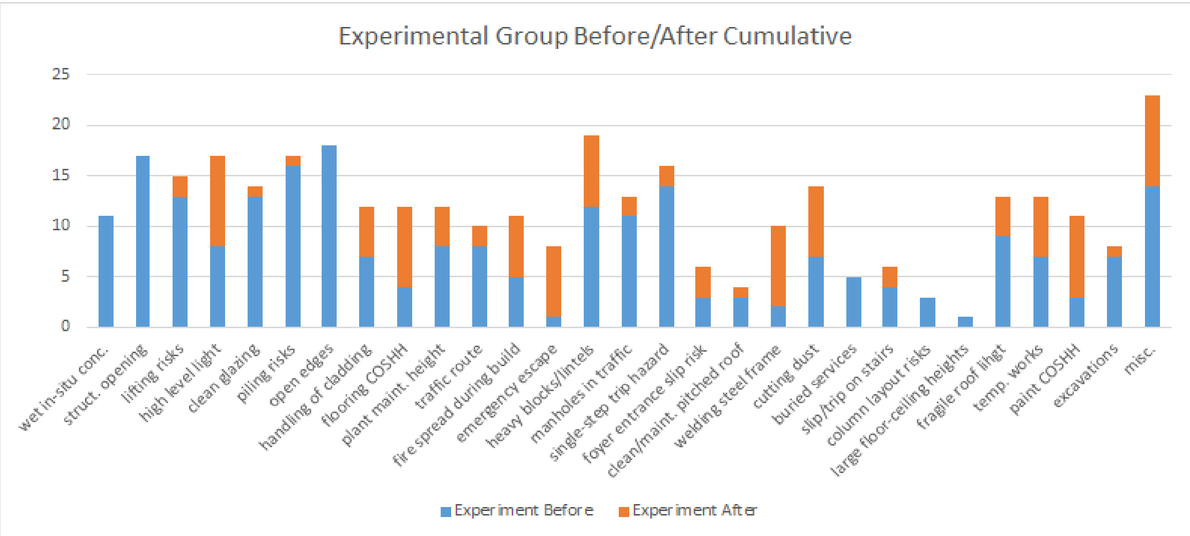

FIG 11: Experimental group number of hazards, before/after, cumulative

The hazards identified by the control group (before and after) are shown in Figure 12. This constitutes a total of 260 hazards (233 before + additional 27 after). The greatest increases in hazards identified for this group were: cutting dust (n. 4); wet in-situ concrete (n. 3); paint COSHH (n. 3). The uplift in number of hazards identified by the control group amounts to 12% of the original number as a result of searching the web, compared to the 45% rise for the experimental group.

Filtering different groups (novice and expert) by experimental and control groups can provide further insights. However, some filters at this level of analysis did not produce much data for comparison. Specifically, the expert designers seem to have demonstrated a comprehensive understanding of the hazards presented in the drawings. But comparing the groups still proved interesting.

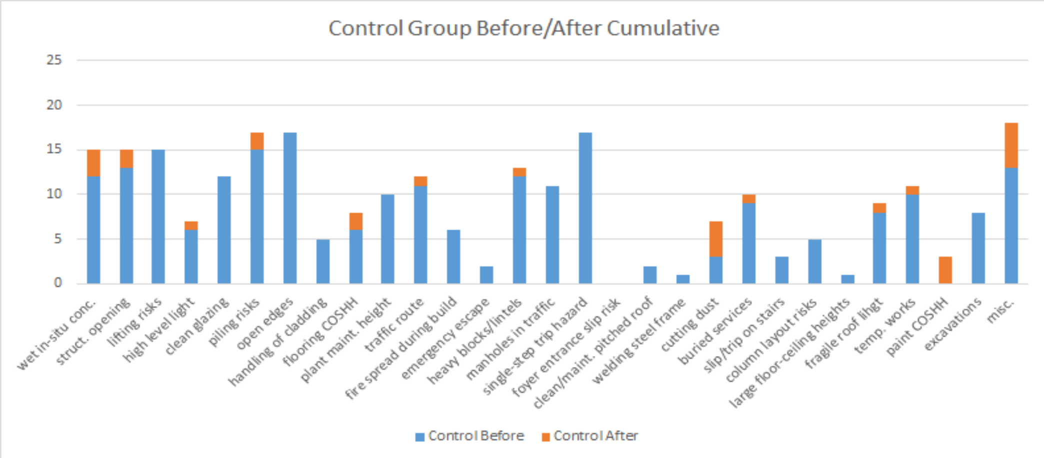

FIG 12: Control group number of hazards, before/after, cumulative

Figure 13 shows additional hazards identified by novice designer's post-intervention. This includes twin bars for each hazard-type; comparing the novice-experimental group (n. 70 additional hazards) with the novice-control group (n. 35 additional hazards). Visually, the bars for the novice-experimental group show better results, with more hazard-types (n. 16 more) identified post-intervention than the novice-control group. Conversely, hazard-types for the novice-control group improved at a better level than the novice-experimental group on only two occasions. There were four occasions where increases are tied between the two groups.

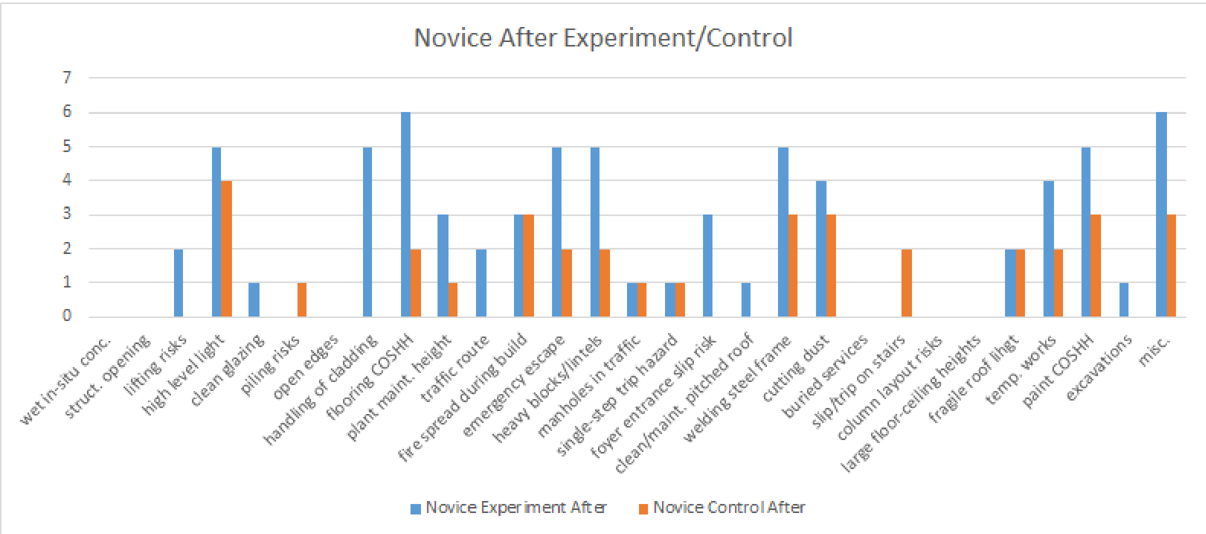

FIG 13: Novice number of hazards after intervention, experiment/control groups

Figure 14 shows additional hazards identified by expert designer's post-intervention, comparing the expert-experimental group with the expert-control group. The experimental group identified 18 hazards post-intervention, compared to the control group who only identified a further nine hazards. Although there are few examples to compare at this level of filtering, it can be seen that there are more bars for the expert-experimental group (n. 10) than the expert-control group (n. 7), indicating a wider spread of hazards identified for those using the digital tool during the intervention.

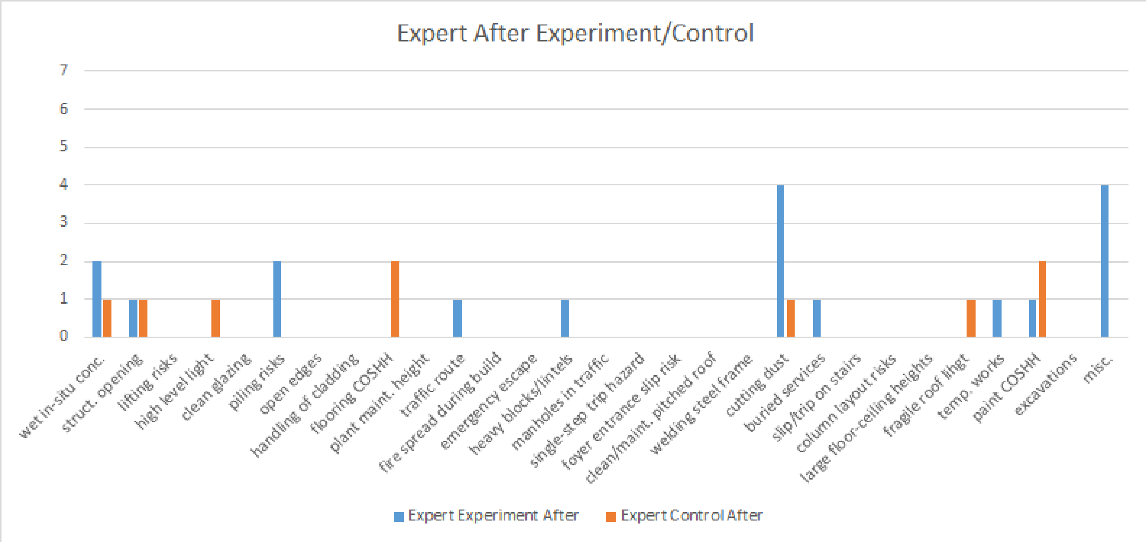

FIG14: Expert number of hazards after intervention, experiment and control groups

The average (mean) number of project-specific hazards identified per designer was analysed for various groups. Figure 15 shows the change, from pre to post intervention, for all designers in the sample. This shows a clear rise in the mean hazard numbers for the experimental group, above that of the control group. The pre-intervention mean values for experimental and control groups were 11.7 and 11.75 respectively (not statistically different). However, the experimental group increased to 16.95 post-intervention, whilst the control group increased to only 13.1. A Mann-Whitney statistical test for the difference between the two groups post-intervention returned a p-value of 0.017 (1-tailed). A Wilcoxon Signed-Ranks for the experimental group confirms a statistically significant change ($Z = -3.829$, $p < 0.001$), rejecting the null hypothesis (that designers will not improve their OSH effectiveness after using the digital tool).

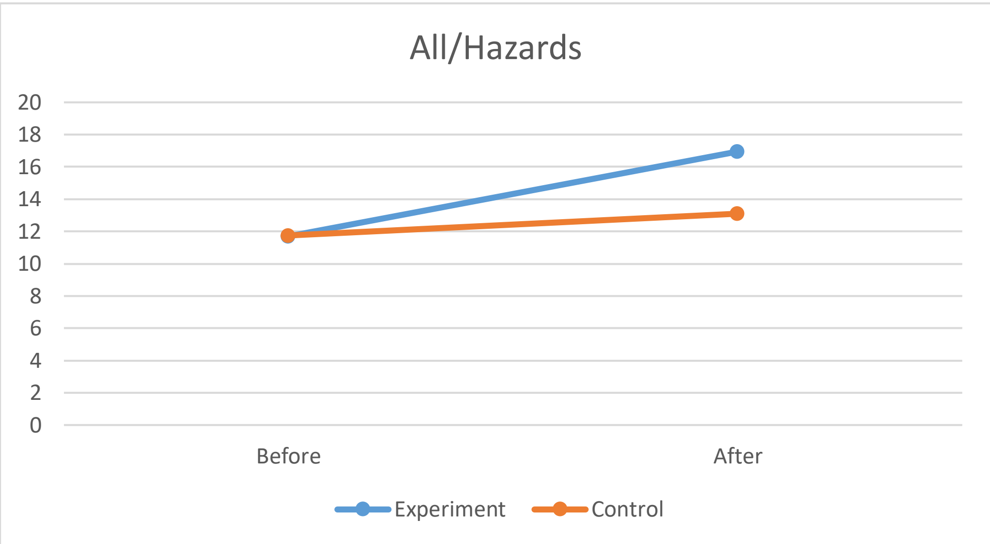

FIG 15: Mean hazard numbers, experiment/control

The data for novice and expert groups are shown in Figure 16. The graphs indicate what was anticipated i.e. novice designers identify (on average) less hazards than expert designers pre-intervention, but increase post-intervention to near expert levels, whereas experienced designers show little increase as their average was already high to start with.

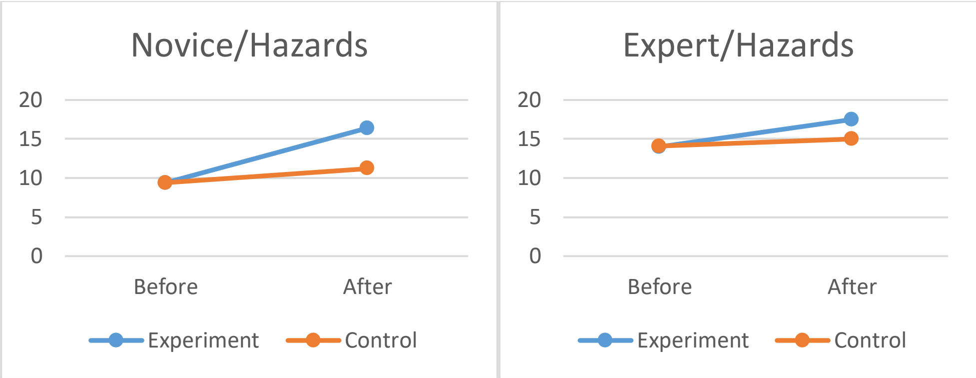

FIG16: Mean hazard numbers, novice and expert experiment and control

The novice groups (experimental and control) both had a mean of 9.4 pre-intervention. The novice experimental post-intervention mean was 16.4 (within group: Z = -2.810, p = 0.001) and the corresponding control group was only 11.2 (between groups: p = 0.018), being statistically significant. The expert groups (experimental and control) pre-intervention, were 14 and 14.1 respectively, rising to 17.5 and 15. This small post-intervention rise was still statistically significant (Z = -2.670, p = 0.002). However, the difference between experimental and control groups was not (p = 0.152) meaning the null hypothesis could not be rejected. This could mean the difference was not great enough to satisfy the test for the sample size, but another plausible explanation could be that expert designers didn't gain the same level of benefit as novice designers to distinguish them enough from the control group (as demonstrated by the small gap between experimental and control groups in the right hand graph of Figure 16).

The main reason for the two graphs in Figure 16 being side by side is to show that the novice experimental group's mean value surpassed the expert control group post-intervention. It was also closer to the higher expert experimental group mean than pre-intervention, as anticipated. The mean scores for project-specific controls recommended by designers was analysed. Figure 16 shows the change, from pre to post intervention, for all designers in the sample. This shows a clear rise in the mean 'risk control scores' for the experimental group, above that of the control group (predictably, a similar result to the mean hazard numbers). The pre-intervention mean scores for experimental and control groups were 34 and 35.6 respectively (not statistically different). However, the experimental group increased to 55.85 post-intervention, whilst the control group increased to only 39.1. The between groups test post-intervention returned a p-value of 0.002 (1-tailed). The within group test confirms a statistically significant change (Z = -3.825, p < 0.001), rejecting the null hypothesis.

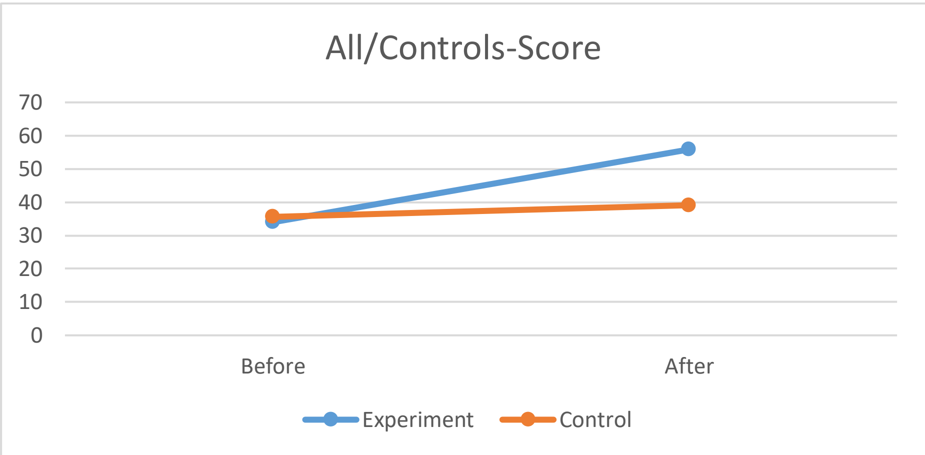

FIG 17: Mean controls-score, experiment/control

The data for novice and expert groups are shown in Figure 18. The graphs indicate what was anticipated in line with the hazard results i.e. novice designers had (on average) lower risk control scores than expert designers pre-intervention, but increase post-intervention to near expert levels, whereas experienced designers show less of an increase as their average was already high to start with.

The novice groups (experimental and control) had means of 24.9 and 28.5 pre-intervention. The novice experimental post-intervention mean was 53.8 (within group: $Z = -2.805$, $p = 0.001$) and the corresponding control group was only 32.1 (between groups: $p = 0.007$), being statistically significant. The expert groups (experimental and control) pre-intervention, were 43.1 and 42.7 respectively, rising to 57.9 and 46.1. This post-intervention rise was statistically significant ($Z = -2.670$, $p = 0.002$). However, the difference between experimental and control groups was not ($p = 0.074$) meaning the null hypothesis could not be rejected. This repeats the result experienced with the hazard means and could likewise mean the difference was not great enough to satisfy the test for the sample size, or (as per the hazards) that expert designers didn't gain the same level of benefit as novice designers to distinguish them enough from the control group (as demonstrated by the smaller gap between experimental and control groups in the right hand graph of Figure 18).

FIG 18: Mean controls-score, novice and expert, experiment and control

The two graphs in Figure 18, side by side shows again (as per the hazard graphs) that the novice experimental group's mean score surpassed the expert control group post-intervention. It was also closer to the higher expert experimental group mean than pre-intervention, as anticipated.

4. CONCLUSIONS AND FURTHER RESEARCH

The overall results clearly demonstrate that use of the multi-media digital tool leads to improved hazard identification, in terms of number and scope of hazards. The digital tool's success is partly due to its visual format; in contrast to e.g. the HSE website, which generally lists hazards in bullet points or tables. This supports underpinning theories on the merits of visual methods of communicating OSH information (Hare et al., 2013; Lingard et al., 2015; Zhang et al., 2015).

The narrowing of the gap in hazards identified, between novice and experienced designers, was as expected. The pre-intervention hazards for the experts was 140 for experimental group and 139 for control group. The novice experimental group figures were 94 pre-intervention and a further 70 post-intervention. This confirms that 164 hazards were identified in total by novice designers exposed to the digital tool, which surpasses the pre-intervention figures of the experts (140).

The increase in mean hazards identified in the experimental group proved statistically significant and the null hypothesis when compared to the control group was rejected. This analysis provides confirmation of what the absolute hazard numbers suggest, that the post-intervention results are not down to chance but are most likely the result of exposure to the digital tool. The findings in relation to the tool's impact on mean hazard numbers for novice designers compared to experts showed conclusively that novice users benefited from using the tool. However, the tests for expert users were not so clear cut. Similar test results were replicated for the mean risk controls score, once again giving uniform results for novice designers but not for experts. The expert experimental group still showed visible increases on both mean hazards/controls graphs compared to the control group, therefore it can be concluded that it is still of use to expert designers but not to the same extent as for novice users. It may actually be worthwhile, if the digital tool is developed further, for expert designers to contribute to the content of the tool for the benefit of newly graduated (novice) designers as discussed in Metaxiotis and Samouilidis (2000).

The research has demonstrated that the digital tool and related materials are of most use to novice designers, such as students and new graduates. Adoption of the research outputs should foster long-term improvements in how new designers approach their designs with regard to DfOSH and their duties under the CDM Regulations. The digital tool and hazard drawings need to be shared with tutors and trainers of architectural and engineering professions.

Integration of the tool with BIM technology would provide an ideal opportunity to further develop and test the theories around visualisation and the application of knowledge databases through visual means. This may also help to determine additional strategies to help designers gain more from use of the tool.

The hazards database and digital tool also provide a format more accessible than other similar databases on the internet, for sharing good practice. The recent rise of BIM technologies (Kumar, 2015) and processes make it possible to incorporate the hazards database within an integrated design system which can assist a designer in designing for OSH in much the same way as outlined in this paper without the need to using a separate database outside of the design system. In addition, other recent developments around Semantic Web technologies like linked data can assist a designer in retrieving the kind of multimedia data (images etc.) stored on the web (like the HSE website) easily into whatever systems they may routinely use in their design activities. Linked data allows data to be retrieved from distributed sources regardless of their formats. A major bottleneck in retrieving data from other sources has been the various data formats used by the respective sources which may not align with that of the retrieving system. Linked data technology overcomes this major challenge and is fast gaining popularity in different applications in various domains (Pauwels et al. 2017). The recommended 'open' format (like a wiki) with designated gatekeepers e.g. Institution of Occupational Safety and Health (IOSH) Construction Group, will allow experienced designers to share their knowledge and help the next generation of designers so that such knowledge is not lost.

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