Building Safely by Design: Interim Report

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Executive Summary
This report describes the progress to date on the ‘Building Safely by Design’ project. The aim of the research is to identify effective modes of interaction between builders and designers, with the aid of a virtual reality tool as a catalyst for their conversation. In a series of ten experiments we will facilitate their collaboration to design safe construction processes in an immersive virtual environment. We are currently piloting this experimental set-up. At the start of the research we reviewed the latest statistical data and policy reports to identify construction safety issues as well as reviewing the state-of-the-art academic research on digital tools to support safe construction processes. We have worked with international and industrial partners in the experimental design, 3D model preparation and scenario creation and gained ethical approval for the work. Our next steps are to run the experiments in summer 2011, to analyse the resulting data and to disseminate the findings of the work to relevant industrial and academic audiences.
1. Introduction

1.1 Background and aims

The research project ‘Building Safely by Design’ (March 2010-February 2011) aims to: *identify effective modes of interaction between builders and designers in which they collaborate, with the aid of a virtual reality tool as a catalyst for their conversation, to design safe construction processes*. The work is conducted within the Design Innovation Research Centre at the University of Reading and funded by the Institution of Operational Safety and Health (IOSH).

A motivation for this research is the exceptionally high rate of accidents and fatalities in the construction industry, compared with the other main industrial sectors in the UK (HSE 2010a). The Construction Design and Management (CDM) Regulations require designers to minimize the hazards associated with construction (HMSO 2007). Hence, designers are obliged to consider safety issues in design. The recent inquiry into the causes of fatalities: ‘One Death is Too Many’ provides part of the context for this work (Donaghy 2009; DWP 2010), and we have focused on major causes of fatalities in setting up our scenarios, though we would also hope that the methodology we develop will help address the full spectrum of construction site accidents by raising their visibility at the design stage.

While designers commonly lack practical construction experience, builders have substantial practical experience related to construction safety. If they could share their experience with designers, they could help them address safety issues in their working practices. To address the project’s aim, our research will use an immersive virtual environment to bring builders and designers together to collaborate in the design of safe construction processes.

The progress to date and current status of the work is summarised below. Then Section 2 outlines the experimental design and explains related theories and procedures. Section 3 discusses the scenario creation, describing and illustrating the specific risk and hazard prevention scenarios identified. Section 4 describes the next steps.

1.2 Progress to date

We are currently piloting our set-up in preparation for running ten research experiments in 2011. In these experiments we will bring together builders and designers in the University of Reading’s immersive virtual environment. This is a ‘CAVE’, which allows a stereoscopic display across four walls and is held in the Visualization Centre at the University of Reading. To date we have identified safety issues; developed model-based product and process scenarios; exported them to the CAVE environment; and we are currently in the process of iteratively improving these scenarios.
To identify construction safety issues we reviewed the latest statistical data and policy reports; as well as the state-of-the-art academic research. This review provided the basis for identifying the construction safety issues for scenario creation; and identified recent international studies that develop new methods and applications that use information communication technologies (ICT) to address construction safety. We summarise the findings of this review in a draft paper, which is currently under review at an international journal.

The literature on ICT tools for design in construction safety is limited, with few examples of innovative software development or applications in working practices. This is despite substantial policy interest, notably, in the UK through the CDM regulations, and increasing research focus on design for construction safety in the international research community, for example in work on prevention by design in the USA (Gambatese, Hinze et al. 1997; Szymberski 1997). Approaches to enabling construction risk and hazard prevention include the Design for Construction Safety Toolbox (Gambatese, Hinze et al. 1997) and Construction Hazard Assessment Implication Review (CHAIR) (Workcover 2001). Related research applications include ToolSHed (Cooke 2008) and the knowledge-based prototype system from NNC Ltd (Davison 2003). Our research seeks to build on this work, address some of its limitations, where existing tools are either not ICT-based or not for use in the design phase.

We are informed by the extensive literature on ICT applications for construction safety during the construction phase, using geographical information system (GIS) (Cheng, Kob et al. 2002; Bansal 2010), virtual reality (VR) (Hadikusumo and Rowlinson 2002; 2004), four-dimensional computer-aided design (4D CAD) (Mallasi 2006), building information modelling (BIM) (Sulankivi 2010), radio frequency identification (RFID) (Song, Haas et al. 2006), ultra-wide band (UWB) (Fontana 2004), global positioning system (GPS) (Navon 2005), etc. These technologies demonstrate effective hazard assessment/prevention potentials in hierarchical levels of product, process and operation in construction. In developing our experimental design we consider how design influences construction at different levels from product to operation.

The project involves our international partner Technion in the experimental design, 3D model preparation and scenario creation. Prof. Rafael Sacks and Dr Ronan Barak are conducting related experiments, and have given us access to the safety tools their team has previously developed, including the ‘CHASTE’ database (Rozenfeld, Sacks et al. 2009), which we will use in our experiment. We have had team meetings via video conference and both Prof. Sacks and Dr Barak visited to work with us on the project set-up in May 2010, with Prof Sacks visiting again in December 2010 to work on a joint publication. Through our discussions, we have developed the experimental design to involve a two-stage evaluation: with 1) independent peer review and 2) VR-based 3D/4D co-discovery to identify construction safety problems in a building design. This experiment design is
intended to allow for some comparison of individual evaluations assisted by 2D drawings with collaborative teamwork supported by VR-based 3D/4D modelling. These results will provide useful indicators of the effectiveness of immersive virtual environments in the collaborative work.

In setting up our research experiments we have also worked closely with industrial partners. We have presented progress reports to, and obtained input from the strategic partners of the Design Innovation Research Centre, Arup, Bentley, Fulcro, Halcrow and Vinci. In preparing 3D models and scenarios we have worked particularly closely with Fulcro, a BIM service provider of various building projects. Fulcro provided a 3D hospital model which we have developed and used for scenario creation in the experimental study. We have also interacted with, and obtained feedback from, a broader cross-section of the industry. In July 2010 we visited Sir Robert McAlpine and presented the project to the Design Manager and a member of his team, to get feedback on our early experimental design. We have looked at the approaches to safety on large projects currently under construction, including the London 2012 Olympics, where we talked with the ODA Director of Health and Safety, and CrossRail (the new rail route across London), where there is substantial documentation on health and safety. Dr Whyte attended the Institution of Operational Health and Safety (IOSH) event on “Construction health and safety - adding value” in January 2011, and will ensure that this network is invited to participate in the research and has visibility of its outputs.

In late 2010, we prepared the documents required to obtain University of Reading ethical approval for the experimental study. The ethics application was examined and approved by our research ethics committee in the School of Construction Management and Engineering at the University of Reading in January 2011. According to the processes set out by the ethics process, related documents that we will use in the data collection include an information sheet for participants, consent form, interview protocol and post experiment questionnaire survey. We also had to obtain approval for our letter and advertisement for recruitment of research participants.

We are about to pilot the experimental design with Fulcro, with a visit to the immersive virtual environment and first pilot organized for 7 March 2011. We have conducted a first check of the set-up, bringing other members of the research team, and Prof Mark Clayton, a visiting professor from the Architecture School at Texas A&M, into the model to check the scenarios and give us feedback.

2. Experimental study

2.1 Overview, background and goals

This research addresses the application of digital technologies for better work practices. The literature review shows there has been little previous research on digital applications to help designers address construction safety. We see the effective use of available digital technologies to enable better work
practices being as important as the development of innovative software tools. It builds on the CHAIR method, applying available digital technologies to address construction safety considerations in the design phase.

CHAIR provides a systematic evaluation for the construction, maintenance, repair, and demolition safety issues associated with design. It applies and adapts hazard and operability studies (HAZOPs) (Rowlinson 2005) to develop a process for evaluating occupational health and safety (OHS) risk implications in construction design. The CHAIR consists of a three-stage review by multidisciplinary teams, involving all stakeholders in design, construction, and use of facility. The first review occurs at the conceptual design phase. At this stage, the design is divided into logical components and, for each component, sources of OHS risk are identified and assessed. Taking place prior to construction after the detailed design is completed, the second review focuses on OHS issues arising in the construction and demolition phases of the project, while the third review focuses on maintenance and repair of the facility. The CHAIR method essentially does not rely on any ICT approaches. Nevertheless, it can involve digital technologies into its review processes to deliver an ICT-aided safety design review practice. Leveraging the methodological principles of the CHAIR, we use an experimental approach that brings designers and constructors together around a 3D/4D model, visualizing design to identify and discuss safety issues.

The goal of the experimental study is to identify effective modes of collaboration in immersive virtual environments for construction safety in the design phase, and specifically. Multiple groups, each comprising a designer, a CDM coordinator and a building contractor, will be observed in two stages, as outlined in Figure 1. 8
Figure 1. Experimental procedure for comparing individual safety assessments to multiparty collaborative safety assessments. The group assessment is performed in a virtual reality laboratory setting.

2.2 Stages of the experiment

In the first stage, they will be asked to provide individual assessments of the hazards inherent in construction of a given building: a designer’s peer review, a CDM coordinator interview, and a builder’s design review. In these independent evaluations, the pre-prepared BIM models include a variety of deliberate design pitfalls influencing construction safety. The design pitfalls are derived from the Design for Construction Safety Toolbox (Gambatese, Hinze et al. 1997), which contributes substantial design suggestions for creating design error scenarios. The design error scenarios in the BIM models will be examined first using 2D drawing sets extracted from the BIM model; or 3D interaction through a CAD interface.
In the second stage, the participants will review the same project together in a VR laboratory for 3D/4D co-discovery evaluation on the BIM models. In this stage, designers, builders and CDM coordinators bring their knowledge and expertise from their domains to clarify safety issues in a collaborative way. Effective interaction involves designers and builders contributing from their specialities and gain from others’ knowledge in problem solving. Supported by 3D/4D CAD and VR, designers’ concerns about related design pitfalls in the 2D building designs and/or 3D CAD models can be interrogated by builders in dynamic 3D walkthrough and 4D simulation. They serve as a catalyst to create a collaboration context (Zhou, Heesom et al. 2009) and help strengthen their experiences on 3D navigation, walkthrough, and simulation when performing the model based assessment.

A video recording system will be used capture key points during the collaborative evaluation from each party for post experimental analysis. This kind of 3D/4D co-discovery evaluation is able to examine digital technologies’ effects and CDM coordinators’ contributions in promoting multiparty collaboration. Hence we examine how design errors become disclosed through their collaboration in the 3D/4D-VR context.

The independent and collaborative evaluation results can then be compared to show their differences; the results of both stages will also be evaluated against safety analysis performed by applying CHASTE. This experimental study can highlight the effects of relevant digital technologies on collaboration. It builds digital support for what, according to the CHAIR method, would be described as the second review phase for construction safety. Specifically, BIM, 4D CAD, and VR will be applied for construction safety design assessment.

3. Scenario creation and presentation

3.1 Common safety problems in construction

Scenarios have been created to prepare some typical safety problems for design evaluation in the experimental study. The latest report in the UK shows that main causes of fatalities in construction include falls from height; being struck by a moving/falling object; being struck by a moving vehicle; or becoming trapped by something overturning/collapsing (HSE 2009). The scenarios we have created address the two most common situations: falls-from-height, and struck-by-moving-objects.
Figure 2a. Construction Sector Fatal Database and b. Fatal accidents by Total Falls, Source: HSE (2010b)

Figure 2a shows how related work activities such as roofing, structural masonry and finishing cause fatal accidents. Figure 2b shows in more detail the role of scaffolding platforms, edges and openings as well as ladders. These records keep consistent with Design for Construction Safety Toolbox, which includes related hazard prevention criteria. Fatal situations thus can be identified applying prevention criteria from the toolbox, and to be presented by the model as scenarios.

3.2 Design pitfalls in our model

The experimental study adopts a hospital project model from our industrial collaborator Fulcro, as shown in two screenshots in Figure 3.
Figure 3. A hospital project 3D model used in scenario creation, showing MEP services (above) and added scaffolding and crane for one of the scenarios (as described below)

We identify design pitfalls in the model we obtained from our industrial collaborator in relation to 1) roofing, 2) finishes of stairs/railings and ladders, and 3) structural masonry. These typical design pitfalls will be presented to participants in the experiment to check if they can be disclosed through their individual and collaborative assessments.

3.3 Presentation of the scenarios

Given the identified scenarios, 3D visualisation is one approach to presenting them in the VR lab. Although a building design is traditionally illustrated by 2D drawings, using interactive 3D technology can better present design considerations via immersive visualisation. Participants in experiments can perform interactive operations to navigate and walk through the 3D model, and evaluate the designed building model at a product level. In this situation, collaborative participants are expected to disclose more design pitfalls than those in their individual evaluations using relevant abstract 2D drawings or 3D CAD models. Design pitfalls 1 to 6 belong to the product level and should be found in the 3D visualisation.

Applying the more advanced 4D simulation technology, the 3D model can be further presented as a dynamic sequence to mock up a construction process. Its usefulness has been widely discussed and shown in many research projects and applications for solving construction problems including safety. The use of 4D modelling in the experimental study can enable participants to assess the design at a process level, as shown in Figure 4.
Figure 4. 4D modelling scenario

It may help participants disclose safety problems like design pitfalls 7 to 9 that hidden at the product level. Under this circumstance, participants can still walk through for design model evaluation. Nevertheless, the simulated construction process can increase participants’ on-site senses of real construction particularly in the immersive VR context. Collaborative participants are anticipated unveiling extra design pitfalls compared with those of the 3D visualisation condition.

Figure 5. Scenarios in the CAVE
These static and dynamic scenarios have been exported into the CAVE for iterative improvement and experiment preparation as shown in Figure 5. These are being used in the pilot tests, which are examining both the suitability of the models and of the experimental processes.

4. Next steps

4.1 The experiments

The experimental study is arranged in a form of workshop, in which we will invite ten groups of designers and builders to take part, together with CDM coordinators where possible. Dates for the first of these workshops are scheduled for Tuesday 24 May, Tuesday 28 June and Tuesday 26 July 2011. In accordance with our experiment design, the designers, CDM coordinators and builders will perform independent peer review and VR-based co-discovery respectively to evaluate the building design. The prepared scenarios will contribute to measure whether or not they can disclose similar design pitfalls, and to what extent they can unveil potential construction risks and hazards. In the VR-based co-discovery session, participants will have chances to get familiar with input devices for walking through the 3D virtual building, before we investigate the effective modes of collaboration between them.

4.2 Research validation and reporting

As described above, substantial work is being done at this stage in the project to ensure the validity of the experimental data. As shown in Table 2, the project will continue pilot testing to examine and refine the experiment in March and April, before the main data collection phase. The processes used may be altered to reflect this peer review and industry input.

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<tr>
<th>Table 2. Project plan, with completed work to end February 2011 (in grey) and forward delivery plan</th>
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<td><strong>Tasks</strong></td>
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<td>IOSH Milestones</td>
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<td>Literature review</td>
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<td>Models obtained &amp; developed</td>
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<td>Scenario creation</td>
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<td>UoR Ethics approval obtained</td>
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<td>VR lab setup &amp; pilot</td>
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Once the experiments have been conducted, the data analysis will examine experiment results from independent evaluations, multiparty collaboration, and automated design analysis. Experimental data includes the cumulative time spent focused on each physical design object; cumulative time spent on each safety issue; number and degree of design changes; and number and nature of new understandings of safety issues gained from the conversation.

The research findings will be summarized in papers for journal publication and industrial workshops and seminars. One publication has been submitted for review, and another is in preparation for the international conference CIB W099: Prevention: Means to the End of Construction Injuries, Illnesses and Fatalities. A final report will be submitted to IOSH in February 2012.

References


