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3. Research Methodology: Is the paper's argument built on an appropriate base of theory, concepts, or other ideas? Has the research or equivalent intellectual work on which the paper is based been well designed? Are the methods employed, robust, defendable and appropriate?

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Contents

Original Research Articles

DESIGN CREATIVITY: Future Directions for Integrated Visualisation

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Abstract
The Architecture, Engineering and Construction (AEC) sectors are facing unprecedented challenges, not just with increased complexity of projects per se, but design-related integration. This requires stakeholders to radically re-think their existing business models (and thinking that underpins them), but also the technological challenges and skills required to deliver these projects. Whilst opponents will no doubt cite that this is nothing new as the sector as a whole has always had to respond to change; the counter to this is that design 'creativity' is now much more dependent on integration from day one. Given this, collaborative processes embedded in Building Information Modelling (BIM) models have been proffered as a panacea solution to embrace this change and deliver streamlined integration. The veracity of design teams' "project data" is increasingly becoming paramount - not only for the coordination of design, processes, engineering services, fabrication, construction, and maintenance; but more importantly, facilitate 'true' project integration and interchange – the actualisation of which will require firm consensus and commitment. This Special Issue envisions some of these issues, challenges and opportunities (from a future landscape perspective), by highlighting a raft of concomitant factors, which include: technological challenges, design visualisation and integration, future digital tools, new and anticipated operating environments, and training requirements needed to deliver these aspirations. A fundamental part of this Special Issue's 'call' was to capture best practice in order to demonstrate how design, visualisation and delivery processes (and technologies) affect the finished product viz: design outcome, design procedures, production methodologies and construction implementation. In this respect, the use of virtual environments are now particularly effective at supporting the design and delivery processes. In summary therefore, this Special Issue presents nine papers from leading scholars, industry and contemporaries. These papers provide an eclectic (but cognate) representation of AEC design visualisation and integration; which not only uncovers new insight and understanding of these challenges and solutions, but also provides new theoretical and practice signposts for future research.

Keywords: *Collaborative Working, Building Information Modelling, Design Visualisation, Decision Support Systems, Innovative Design Interfaces*

INTRODUCTION

Construction and engineering projects are increasingly becoming more complex, often engaging new business processes and technological solutions to meet clients' requirements. These new processes and allied technological solutions often require parallel improvements to be made, supported by appropriately skilled professionals and operatives (Arif *et al.*, 2012; Goulding *et al.*, 2014a). Building Information Modelling (BIM) has demonstrated the need for integrating collaborative design teams' "project data", to not only help coordinate the design, engineering, fabrication, construction, and maintenance of various trades, but also facilitate project integration and interchange (Goulding & Rahimian, 2012). Given this, numerous potential benefits have inspired several countries to consider the implications of implementing BIM Level 3 (Cloud) as an innovative way of further enhancing the design, management and delivery process, *ergo* aligning needs and expectations towards a fully Integrated Project Delivery approach (Goulding *et al.*, 2014b). A number of innovative approaches are starting to pervade the market, including: virtual/augmented reality, mobile and web-based platforms, laser scanning and photogrammetry technologies, 3D printing etc. Whilst these are particularly beneficial for integrating visualisation data, and promoting the maxim of sharing/integration; prototyping and testing (especially with geographically dispersed users) still has many challenges to overcome. Establishing advanced design representation futures is therefore considered essential. This Special Issue enables readers to appreciate some of these nuances, particularly to envision future foresight into future digital tools, their expected operating environments, and the training requirements needed – particularly for design professionals. This Special Issue highlights how these improved virtual delivery processes and technologies affect the designed products, including the design procedures, production approaches and subsequent implementation (construction). In doing so, it evaluates how digital design (especially in virtual environments) can support AEC design organisations to optimise project deliverables.

This Special Issue encouraged submissions on foresights, development and application of advanced digital tools within the AEC sector to highlight existing theoretical, practical and technical gaps within: design-practice, design-production, design-construction, and design-facilities management. This embraced collaboration and implementation needs of multi-disciplinary team members, including: conceptual and theoretical frameworks, technological innovation and empirical research on designed products, and their tools and processes (including organisational behaviour). Nine papers were accepted, representing world-leading scholars in the field – the findings of which present new critical debate and discourse on design visualisation and integration.

Soetanto *et al.* (2015) used questionnaire surveys, focus groups, observation of online meetings, and personal reflections to identify key success factors - leading to the development of guidance for international collaborative design projects, via the implementation of collaborative design courses in the UK and Canadian universities over three academic years. Research findings revealed the significance of the perceived risk of collaboration and a difference in preferred communication mode between architects and civil/structural engineers. This work emphasised the impact of training in the subject discipline, and that the opportunity for co-located working had helped the development of trust. This paper provides guidance for Built Environment educators wishing to implement collaboration into courses.

Yuan *et al.* (2015) reflected on the challenges and risks associated with construction labour working on or near temporary structures. It provided statistics on fatalities and capital losses for companies. This paper introduced Cyber-Physical Systems (CPS) as a viable solution for preventing potential structural hazards. Evidence from seminal literature was used to inform findings, which advocated CPS applicability in temporary structures, along with potential benefits associated with structural monitoring. A conclusion drawn was that CPS had significant potential to address safety and structural problems of temporary structures. The authors provided a scaffolding system exemplar application scenario to show how CPS worked in structural monitoring, including the requirements and system architecture.

Kim *et al.* (2015) emphasised the link between the effectiveness of visual displays and the quality of 'sense of presence' in immersive VR environments. This proffered that there was a gap in research for analysing how presence was associated (from a multi-users' quality of communication perspective) within the context of AEC. In order to address this issue, they conducted an exploratory study on social interaction, with the remit of improving the presentation and communication of complex data through immersive simulation techniques. Research findings from seminal literature emphasised the importance of embedding key concepts such as presence and immersion, as these were seen as pivotal factors that influenced communication. A Hub for Immersive Visualization and eResearch (HIVE), was introduced, supported by a conceptual framework for enabling multi-users to understand how to implement social interaction in a system efficiently – especially to determine whether a visualisation system could support communication effectively. Findings proposed additional research in the context of cognitive factors (within shared environments) and the need to validate this framework.

Maftei and Harty (2015) presented findings from a study based on the design of a new hospital using immersive Virtual Reality (VR) technologies. They used the concept of reflective practice (Schön, 1983) supported by video-based methods to analyse the ways design teams approach and employ collaborative design work using a full scale 3D immersive environment. This paper revealed some unique aspects of design work in this environment. Research findings highlight that rather than enhancing or adding to our existing understanding of design through paper based or non-immersive digital representations, that such new immersive and interactive design interfaces have the potential to challenge or 'surprise' designers as they experience immersivity in full-scale.

Shih *et al.* (2015) introduced new insight on the impact of interfaces with design cognition. They presented the results of a preliminary protocol study on the cognitive behaviour of architects, to better understand the similarities and differences using Sequential Mixed Media and Alternative Mixed Media (AMM) approaches. This work employed protocol analysis methodology and coded video recordings of participants working on different projects (based on the Function-Behaviour-Structure coding scheme). Research findings present the views of participants on their switching behaviour when transiting between different types of media; noting that despite some challenges, these switches could make it possible for designers to integrate different approaches into one design medium to facilitate design processes within AMM design environments.

Wang *et al.* (2015) focused on learning styles, advocating that changes triggered by the digital paradigm shift affected perception, and that users' experience was not always favourable. This study investigated the impact of VR technologies on the learning style preferences by studying 245 architecture and construction students over a two-year period. Results indicated that when virtual reality applications were used in teaching and learning, that learning behaviour favoured a more concrete 'experiential' mode of learning, with a preference or tendency toward the Accommodator learning style. However, whilst novel visualisation techniques were examined, a caveat of note identified that as VR becomes more deeply embedded in teaching and learning programs, studies of learning style preferences should become more representative than a single technology per se.

Park and Kim (2015) presented a case for employing automatic methods for checking design quality and compliance with building codes (as opposed to conventional manual control methods), as this was considered particularly important with increased project complexity. This work also highlighted the importance of applying semantics in the checking process, examining BIM in the context of design teams and regulatory bodies – especially useful for decision-making and evaluation with rich data and formal descriptions. A BIM-based quality checking process case study was presented to resolve building health and safety issues. Research findings suggest that BIM-based quality checking processes can be successfully employed to improve safety management.

Megahed (2015) acknowledged the progressive increase in demand for use of BIM in historic buildings; noting that BIM can present an accurate virtual model of a historic building in order to maintain the building through its entire lifecycle, including demolition. This approach, known as HBIM, represents a new paradigm within architectural heritage; the remit of which can be used for creating, conserving, documenting, and managing complete engineering drawings and information. This paper presents an overview of the HBIM concepts, including surveying and representation techniques applied to support integration – including complexity associated with built heritage resources. A theoretical framework is presented for discussion, highlighting the different aspects of historic preservation and management through a smart open platform.

Jamaludin *et al.* (2015) highlight the dynamics of daylighting within a residential college building and internal courtyard arrangement. This research was supported by various field measurements to complement computer simulations. The field measurements involved eight unoccupied student rooms, selected as samples to represent ten scenarios and orientations (viz the level of radiation and penetration of sunlight). Various visualisation and simulation techniques are presented for discussion, including: different amounts of daylight in specific room scenarios. Research findings highlight that rooms can be augmented to consume less electricity usage, particularly for lighting purposes, to enhance the comfort of indoor living space.

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KEY SUCCESS FACTORS AND GUIDANCE FOR INTERNATIONAL COLLABORATIVE DESIGN PROJECTS

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Abstract

In the built environment (BE) sector, the co-creation process of design demands understanding of requirements (as viewed by parties involved), mobilisation of tacit knowledge, negotiation, and complex exchange of information. The need to collaborate over distance has further exacerbated the complexity of the process, and, in itself, represents a significant challenge for BE professionals who are increasingly expected to undertake this process within globally distributed virtual teams. The research aims to identify key success factors and develop guidance for international collaborative design projects, via the implementation of collaborative design courses in UK and Canadian universities over three academic years. Questionnaire surveys, focus groups, observation of online meetings, personal reflections provided data for the analysis. The findings reveal the significance of the perceived risk of collaboration and a difference in preferred communication mode between architects and civil/structural engineers. These findings suggest the impact of training in the subject discipline, and that the opportunity for co-located working has helped the development of trust. The guidance is aimed at BE educators who wish to implement this activity in their courses.

Keywords: *collaborative design, communication mode, virtual team*

INTRODUCTION

In the early design process of built facilities, communication between parties from different disciplines has potentially significant impacts on downstream activities, and on the creation of added value. At this early stage, design problems are by nature often not clearly defined and can be characterised by vague initial requirements, partially specified goals and indefinite possible solutions (Tezel & Casakin 2010). To produce a satisfying solution requires an iterative and creative collaboration between parties. This co-creation process of design involves mobilisation of knowledge which is often tacit and embedded within individual disciplines. The collaboration process has been the subject of research in the last two decades, which have produced process models and IT tools (e.g. Kagioglou *et al*., 1998; Austin *et al*., 2000; Bouchlaghem *et al*., 2005), and suggested behavioural change and innovative procurement arrangements to enable better collaboration (e.g. Akintoye & Main, 2007). Despite some improvements, poor communication remains one of the root causes of mediocre performance in design and construction (Dainty *et al*., 2006).

Advance developments in information and communication technologies (ICTs) have made possible real time, distanced communication between parties in different locations. Increasing international collaboration in the building industry means that more professionals will be required to work in virtual teams within an online platform. To ensure effective performance, these parties have to manage content space (i.e. activities to be undertaken, problems to be resolved) and relational space (i.e. social interaction with possible conflicts and opportunities). Importantly, the team needs to achieve a high level of collaboration awareness (Leinonen *et al*., 2005). This online mode of working is particularly challenging given the complex design process, requiring rapid exchange of information, in addition to strongly ingrained disciplinary divisions between parties. This is inherent within the modus operandi of the industry, and has created structural and cultural barriers which inhibit integration, resulting in inefficient processes and sub-optimal solutions to the client's problems. Arguably, it is also reflected in the current education system of the built environment (BE) subjects, reinforcing the culturally-ingrained 'disciplinary silo' in the construction industry (Banwell 1964, Latham 1994, BAF 2015).

Multi-disciplinary working presents a significant cognitive challenge for students as this requires a comprehensive understanding of the interests and orientation of the other subject disciplines, and the need to fit these in a 'jigsaw' of knowledge to produce the constructed facility. This understanding may improve as individuals obtain more experience from their exposure to workplace practice. Further, there are attitudinal requirements that will facilitate successful multi-disciplinary working, for example, a willingness to consider and accept the ideas of others, level of trust, preference for working in teams, the ease of establishing relationships with others in the team, which are very much related to culture at functional, organisational and national levels. These can all be better acquired through experiential learning, rather than infused through the process of knowledge transmission during a lecture session. Another important challenge is the potential mismatch of preferred communication modes between parties from different disciplines. Due to inherent cognitive processing, individuals may have preferences for the way they wish to receive and give information. The same information can be represented in different ways; the choice is made by individuals based on their cognitive process of sense-making. The mismatches between preferred and actual communication modes may lead to less effective exchanges of information, misunderstanding, disputes and stresses. Knowledge of learning styles would permit individual learners to adopt appropriate strategies (i.e. use of representations) which can facilitate better understanding and communication. On the other hand, tutors would also be able to adopt the most effective teaching methods for the learners. Learning styles would also allow an evaluation of the impact of training in the BE disciplines; whether students in different disciplines may exhibit different learning styles, and whether they prefer certain representations of information. Currently, there is little knowledge on the relationship between BE subject disciplines and preferred communication mode.

The recently published report by BIM2050 group (2014), commissioned by the UK Construction Industry Council, illustrates the future of working in the BE sector, and identifies the education and skills requirements to meet future challenges to the year 2050, in the context of global competition and uncertainty, increasing complexity of built facilities, depleting resources and emerging technologies. The report highlights the ever-important integration in the design and construction process, suggesting that a future mode of working requires graduates who can work across disciplinary and geographical boundaries. In Canada, a survey by Digicon and IBC (2013) suggests that industry growth in the use of Building Information Modelling (BIM) technology relies on the education of BE professionals. This projection of skills requirements for the 21st century could have profound implications for the provision of BE education. Therefore, there is a need to rethink BE education systems to prepare graduates to harness the opportunity given by emerging technologies to work in a globalised industry. Importantly, BE educators should introduce curricula which can provide BE students with essential experience and skills required to work and collaborate across disciplines, cultural and geographical boundaries. This presents a complex and intricate problem for BE educators, whose main responsibility is to prepare the future professionals for the industry. Despite its significance for industry progress, little is known on how BE educators can implement these curricula more effectively.

Given the above challenges, the key research questions which this paper seeks to address are:

1. What are the factors influencing the performance of collaboration in virtual teams?
2. Is there any difference in preferred communication mode between parties from different disciplines in the building design process?
3. What strategies should be deployed to achieve effective online collaboration? How can these be used by BE educators to incorporate collaborative design projects within the curricula?

To address these questions, research was initiated by implementing an authentic, multi-disciplinary, distanced collaborative design project which mimics industry practice. This paper reports the findings of the investigation of virtual teamwork of final year undergraduate BE students in two institutions in the UK and Canada. They were required to design a building project and collaborate over the internet using various modes of communication including Skype, email, Dropbox and GoToMeeting. They undertook a process of co-creation of a building design over a geographical distance. This design project was repeated in three consecutive academic years. To address the first two research questions, each year, a questionnaire was distributed in two phases at the beginning of the first semester and at the end of the second semester. In the third academic year, the project involved the use of GoToMeeting desktop sharing which permits real time interaction and discussion of building design objects, such as plans, drawings and 3D models. A greater understanding of significant factors influencing collaboration in the virtual teams and preferred communication modes of individuals from different disciplines will help BE educators to develop appropriate strategies to facilitate collaboration and enhance the skills of students. Through observation of meetings, focus group interviews and analysis of individual personal reflections, guidance for effective practice in collaborative building design project was developed. The following sections present a review of relevant literature which provides the underpinning knowledge for the development of the research. A method to identify individual preferred communication modes, collaborative design process, research methodology and methods are described, before the presentation and discussion of findings and the guidance for effective practice in collaborative design projects. Conclusions are drawn to illustrate what the findings may mean for construction education and industry professional practices, and the limitations are described with further research.

COLLABORATIVE DESIGN PROJECT

The collaborative design project is considered part of the problem-based learning which is often equated to inquiry-based learning, project-based project-, product-, process-, people-based learning (Fruchter, 1999). Although these have slightly different meanings, such terms rest on common philosophical ground in that the learning centres around student activities; the students learn more effectively from the activities they undertake and experience first-hand, rather than from listening to traditional lectures. Here, ‘problem’ could be a (hypothetical or real) project, scenario, case-study, research question or similar in a classroom, work-based, laboratory-based or other appropriate setting and for which a range of solutions or responses are appropriate (Wilson-Medhurst, 2008). Collaborative activities enrich the learning process, allowing the learners to share and enhance knowledge in a group work setting, and represent the practice of multi-disciplinary design in the industry. However, the idea of a collaborative design project is not new, and is a feature of BE courses around the world. For example, Barry *et al*. (2012) describe the development of the capstone design course in Purdue University, which has been team-taught since the early 1960s. Some recent examples, such as Bhandari *et al*. (2011), Peterson *et al*. (2011), Soibelman *et al*. (2011), Wolcott *et al*. (2011), Korkmaz (2012), Stanford *et al*. (2013), Solnosky *et al*. (2014), are varied in their focus with different objects of design, supporting technologies, disciplinary composition and locations of team members, previous training and education levels (Soetanto *et al*., 2014). Most were implemented within one institution which makes possible regular offline (face-to-face) communication between students (e.g. Tucker & Rollo, 2006; Barry *et al*., 2012; Solnosky *et al*., 2014), but fewer include collaboration between students from two or more institutions from different geographical locations (such as Fruchter, 1999; Hussein & Peña-Mora, 1999; O'Brien *et al*., 2003 and Becerik-Gerber *et al*., 2012; Soetanto *et al*., 2014). Previous research studies have considered the effectiveness of distributed project teams (Gaudes *et al*., 2007; Kankanhalli *et al*., 2007) and the impacts of distance collaboration on the outcome of a design process (Dossick *et al*., 2015).

The challenges of communication in a distributed team

Geographical separation of the team members prevents face-to-face communication and interaction which is often a necessary condition in the problem solving sessions to achieve an optimum design outcome. Despite extensive research conducted to understand how and why teams achieve desired outcomes, relatively little is known about the elements that determine and influence virtual team performance (Lee-Kelley & Sankey, 2008; Algesheimer *et al*., 2011). Gaudes *et al*. (2007) compiled a comprehensive list of factors that contribute towards the effectiveness of virtual teams, and grouped them against an inputs-processes-outputs model and facets of individual, team, leader, organisation, project, and technology. However, there is no pointer to which factors are the most appropriate for a certain context, and arguably the same list could also be applicable for traditional co-located teams. Further, they highlighted the need to consider the context and systemic association between micro (i.e. individual, team) and macro (i.e. organisation, company in the supply chain) levels when considering factors influencing the effectiveness of a virtual team.

The literature on virtual teamwork shows consensus that trust is the critical factor for maintaining team effectiveness. In virtual collaboration, the word 'trust' is interpreted as perceptions of trustworthiness (Hardin, 2000 c.f. Zolin *et al*., 2004). Mayer *et al*. (1995) and Zolin (*ibid*.) recommended three dimensions underlying perceived trustworthiness: benevolence, ability, and integrity. As defined in Zolin (*ibid*.), benevolence is the positive perception of the trustee towards the trustor (Mayer *ibid*.). Benevolence can be the outcome of parties having successfully aligned interests and goals in the project (Hardin, 2000). Ability is the perception that the trustee has the skills and resources needed to perform the task for the project. A high level of effort (i.e. diligence) does not guarantee success if the party does not have the required skills to undertake the task. In this case, the level of trust may suffer. Trust also depends on the individual perceptions of those in the collaboration. A person having integrity is seen to be more likely to behave in honorable ways and not deceive their co-workers about their intention to meet commitments and expectations (Zolin *ibid*.). Mayer (*ibid*.) and Zolin (*ibid*.) argue that the perception of risk also influences perceived trustworthiness and trust. Thus, when the perceived risk is high, higher perceived trustworthiness may be required to trust the other. Collaborating in a geographically-distributed, multidisciplinary team may impose a higher risk (as perceived by individual members) due to dependence on one another's skills to complete the work, difficulty to know one anothers' work progress, and difficulty in reaching a shared understanding (Zolin *ibid*.; Leinonen *et al*., 2005).

The absence of social interaction in virtual teams is likely to limit the development of high levels of trust, although higher trust and cohesion could be achieved when team members are involved in social interaction earlier in the project (Chidambaram, 1996; Jarvenpaa & Leidner, 1999 c.f. Gaudes *et al*., 2007). In co-located teams, trust is nurtured through personal interactions between members over time, as time would also permit feedback, sharing and support between members, which facilitate team cohesion and develop team identity (Hertel *et al*., 2005 c.f. Gaudes *et al*., 2007). When team members are separated, they are less likely to establish one-to-one relationships (Chinowsky & Rojas, 2003). As trust is developed over time, reduced time for interaction due to financial pressure can thus serve to prevent the development of trust in teams. Several other factors that may contribute to the lack of (the development of) trust are: the different disciplines involved, different working practices (i.e. building standards, regulations, legal framework), and different cultures at functional, institutional and national levels (Zolin *ibid*.). In addition to the transient project-based nature of construction, working in a virtual team does not enable the anticipation of future association which promotes trust and cooperation. Co-location allows teams to foster shared values, expectation, cohesion and increase commitment to an objective (Daim *et al*., 2012). The absence of frequent in-person interaction, aligned expectations and team cohesion may increase the propensity for conflicts between team members (Kankanhalli *et al*., 2007). These conflicts can be further exacerbated by the mismatch of preferred communication modes between individuals from different disciplinary backgrounds, as explained in the following section.

Preferred communication modes

In the building design process, a mismatch in preferred communication mode can hamper the creative process of co-creation of building design, whereby interacting individuals are expected to understand one another's mental schema and maintain a high level of collaboration awareness. Given that the creative design process involves information exchange and learning activities, an individual's learning style would have a strong association with their preference to receive and give information. For example, Demirbas & Demirkan (2003) found the effect of learning styles and the type of representation used to solve design problem on the outcome. Yazici (2005 cited various authors) indicated that individual characteristics such as psychological profile and learning preferences were likely to influence performance. Here, there is a need to define an appropriate learning style inventory to investigate the preferred communication modes of members of multidisciplinary team.

Despite long-term use and popularity of the term 'learning style', there is still disagreement about its definition and relationships with cognitive styles and learning ability, as well as a lack of consensus on what a learning style inventory should include (Leite *et al*., 2010). Kolb's (1984) experiential learning style focuses on the cognitive process of learning style (i.e. how individuals process information in the brain). The VARK (Visual, Aural, Read/write, Kinesthetic) questionnaire was developed by Neil D. Fleming in 1987 as a means to identify an individual's preferred communication modes (Marcy, 2001). In comparison to Kolb's (1984) experiential learning style, VARK focuses particular on identifying the preference of individuals to take in information coming to them and the ways by which they like to convey their information (Fleming, 2015). Fleming & Mills (1992) found that many students attributed their learning difficulties to the form in which course material was presented. That is, some students found they had difficulties learning in situations where the course material was only presented orally, while others reported similar difficulties when the material was primarily in written form. The VARK questionnaire helps users to understand their preferred communication modes, and allows them to reflect, and then develop appropriate strategies to facilitate their own learning. Since it was created, VARK questionnaires have been widely adopted not only in an education context, but also in businesses. Through online surveys since 2001, a large database has been collected and analysed according to the demographic and occupational backgrounds of the respondents. The VARK questionnaire was employed in this case to identify the preferred communication mode and the differences between members of each building design team.

The need for research

Despite its potential benefits, working in geographically-distributed, multidisciplinary teams represents a significant challenge for their members. Previous research studies tend to focus on how their performance differs to that of traditional (i.e. co-located) teams, and attempt to understand the factors influencing the performance of a virtual team. However, given the dynamic of a virtual team, variability of implementation context and approaches adopted (Solnosky *et al*., 2014), the performance of the team over a longer time, its influencing factors and impact are difficult to assess objectively (Becerik-Gerber *et al*., 2012; Soetanto *et al*., 2014). O'Brien *et al*. (2003) and Becerik-Gerber *et al*. (2012) found that remote collaboration is not always successful and often less effective than face-to-face offline meetings. Communication technologies are often blamed for the poor performance of virtual teams, but they are not the root cause of problems; although they could amplify the discrepancy and other barriers which already exist, such as the professional ethos of virtual team members (Soetanto *et al*., 2014). Such issues are further exacerbated by the lack of guidance on how to implement a successful collaborative design project. The inconsistency of the outcomes and lack of implementation guidance do not provide sufficient confidence for individuals to work in virtual teams. Ultimately, this could prevent individuals from adopting virtual teamwork, which has the potential to be an effective cost-saving strategy.

The main contribution of this paper is to identify the key success factors influencing multi-disciplinary, distributed team interaction and collaboration, and to present a guidance regarding an international collaborative design project. Specifically, the research aims to understand how the perceptions of collaboration and preferred communication mode differ between members of a multidisciplinary virtual team. A greater understanding of these differences will allow the identification of conflicts, the evaluation of the impact of disciplinary training, and the development of appropriate strategies to enhance performance. In the long-term, this knowledge will allow more consistent outcomes to be obtained. Simultaneously, the guidance will not only facilitate this goal, but also help BE educators to implement effective online collaborative design projects in their curricula. A description of the collaborative design process adopted in the research is explained in the following section.

COLLABORATIVE DESIGN PROCESS

International teams were formed from local groups of four students in each participating universities. These groups then worked on a project brief, which was developed collaboratively by tutors, based on a hypothetical project scenario. The project brief included (i) description of intended purposes of the building, requirements of facilities (e.g. rooms, area, environmental aspects), site location, investigation and constraints (relationships with the existing building and facilities in the surrounding area), operational requirements of group work (i.e. guidance of meetings, roles of individual student), assessment of tasks with detailed requirements for each project phases, and peer assessment using the Web-PA system (see Wilkinson & Lamb, 2010 for description of Web-PA). In addition to these, design guidance regarding building standards, structural design codes, posters and presentations were also provided. Throughout the academic year, the tutors were present, not only as the client, but also to support the collaboration on a consultancy basis and, sometimes, to act as a mediator should relationship issues in the teams arise. The mediator has an important role in the process of virtual collaborative learning (Soetanto *et al*., 2014).

The teams conducted weekly meetings, and appointed a team leader and secretary that were rotated every four or five weeks, thus enabling each member of the team to carry out each role. The team leaders chaired the weekly project meeting, monitored and coordinated the work of the team, ensured that submission dates were met and generally oversaw the day-to-day running of the project team. The secretary took the meeting minutes, noting any important points discussed, and deputised for the team leader in the event of absence. The individual marks were derived from the group mark, after peer assessment to acknowledge individual members contribution and to ensure fairness. Pedagogical benefits of peer assessment to skills formation in group work is explained in Wilkinson & Lamb (2010).

RESEARCH METHODOLOGY AND METHODS

The research adopted quantitative and qualitative research methods in order to address the research questions. The research takes the position that individuals (as the unit of analysis) have their own perception of collaboration and preferred mode of communication with the others in the team (ontological position). These perceptions could be measured by asking team members (i.e. participants in the research) to express their opinion against a series of statements on a specific attitudinal scale. Data sets combining responses from the participants could then be analysed statistically to explore differences between categories (i.e. groups in the UK and Canada, gender, working experience, implementation phase), to generate new knowledge (epistemological position). To obtain quantitative data, a questionnaire was developed and distributed to participating students. The other goal was to identify a set of good practices for this type of implementation. In order to maximise impact, and provide sustainability for this implementation approach, the research aimed to create a set of 'guidance notes' for subsequent/future practitioners to follow if they also planned to conduct online collaboration with students. This required rich data detailing the students' and tutors' experiences, and using their perceptions of what worked and what did not during the intervention, to build a set of recommendations. In this case, the research position is that certain practices and interventions have an impact of the outcomes of virtual teamwork (ontological position). These practices and interventions are observable through feedback and observation of participants. This feedback and observation were then analysed qualitatively to generate recommendations (epistemological position). The qualitative data were obtained via focus groups, individual reflections, and observations. In combination, these two data sets provided a strong corroboration of the research findings, thereby verifying the results, further justifying this mixed methods approach, and satisfying the research objectives.

A questionnaire survey was conducted in the first two years of the implementation. In each year, the questionnaire was distributed twice: before (i.e. at the beginning of the first semester) and after implementation of design project (i.e. at the end of the second semester). The questionnaire survey sought: (i) background information (including course, gender, working experience), (ii) aspects of distance collaboration and teamwork (such as trust, quality of work, risk, perception on other team members, communication, face-to-face meeting, satisfaction), (iii) VARK questionnaire, which comprises 16 questions (explaining 16 different situations), each with four different answers, that reflect different ways of taking and giving information for the same situation (provided in Fleming, 2015). For questions related to distance collaboration and teamwork (listed in Table 1) , the respondents were asked to express their level of agreement against a four-point scale from 1 to 4 where 1 indicates 'strongly disagree'; 2 'disagree'; 3 'agree'; and 4 'strongly agree'. A neutral middle point ('neither agree nor disagree') was not included to make respondents more discriminating in their responses, and this makes respondents more thoughtful and leads to more precise responses (Garland, 1991). Therefore, the engagement with and accuracy of the scale used by the research may be improved through the use of a four-point scale. The responses to the VARK questionnaire were coded according to corresponding preferred modes (V, A, R or K). The respondents were allowed to choose multiple answers to each question. The responses corresponding to V, A, R, and K were then summarised. The highest score indicates the preferred mode. If there is a tie between two or more modal preferences, the result is considered a double or triple tied preference (Fleming, 2015). A study by Leite *et al*. (2010) confirms the validity and reliability of measures of VARK learning style.

The questionnaires were distributed to all participating students before the project commenced. They were given around 15 minutes to complete it (three pages in total), and responses were collected by tutors immediately. For the purpose of evaluating the consistency of the findings, this design project was repeated in two consecutive academic years. The first year data collection yielded 134 (n1) completed questionnaires, the second year 58 (n2) completed questionnaires. In total, there were 192 (N) completed questionnaires, which were subsequently statistically analysed using descriptive statistics and Chi-square tests obtained from SPSS software. Chi-square tests were used to identify if there were any significant differences between categories of respondents on their perception of collaboration and preferred communication mode. The initial findings with the smaller data set were presented in Soetanto *et al*. (2012a; 2012b). This paper presents findings of analysis from a larger data set which allows more robust conclusions to be drawn.

Table 1: List of collaboration and teamworking statements

Variable	Statement
V1	I need to check to see if the other team members have progressed their tasks as promised.
V2	I need to check the quality of work of the other members.
V3	In group work, I am exposed to higher risk of poor mark / performance.
V4	I feel more rewarded by working in team.
V5	The other team members make my job easier.
V6	The other team members are competent.
V7	The other team members are honest.
V8	The other team members complete work commitments on time.
V9	Communication over the internet is difficult.
V10	Face-to-face meeting is essential for a high performing team.
V11	Conflicts with the team at the other University can be resolved easily.
V12	Information has been communicated effectively.
V13	Information has been communicated via an appropriate medium.
V14	Decision making process has been effective.
V15	I need the other team to complete my work.
V16	Leaders exercise their duties effectively.
V17	I am clear about my role in my team.
V18	Team members are comfortable with each other.
V19	Overall, I am satisfied with working in my team.

In the third year of implementation, the qualitative method was adopted to identify good practices and then develop the guidance for online collaboration. Data were obtained and analysed in three groups of data sets, namely observational analysis of the recordings made by students of their synchronous meetings using ‘GoToMeeting’, focus group interviews in semesters 1 and 2, and analysis of personal reflections of the students. Participating teams were interviewed via focus groups, and required to submit individual reflections and one recording of team meetings via GoToMeeting, in each semester. Each recording lasted about 30 minutes to one hour and was jointly observed by the research team. A total of fifteen recordings (nine from the first semester and six from the second semester) were obtained. During the observation, the research team identified and discussed key issues arising from the observation. Due to the extensive experience of the research team, this not only enhanced the strength of identification and analysis, but also minimised bias. The findings were then grouped in several specific themes. A saturation point was achieved about half way through the fifteen recordings. The findings from the GoToMeeting observations were further informed by the analysis of focus groups and individual reflections. These separate analyses enabled triangulation of the outcomes and provide supporting evidence for the guidance presented here.

RESULTS

Tables 2, 3 and 4 detail proportions of students based on their working experience, gender, and implementation phase categories. From a total of 192 responses, 92 responses were received from Canadian students, and 100 from UK students. Two-thirds (67.9%) had no work experience in the construction industry. In respect of gender, male students represent 59.2% and female 40.8%. The relatively even distribution of responses allows comparison between categories (e.g. comparison of responses between UK and Canada, male and female, working experience, implementation phase) to explore the relationship between categories and the collaboration variables.

Table 2: The number of participating students in each institution and working experience category

Institution	Students with working experience?		**Total**
	No	Yes	
UK University	67 (73.6%)	24 (26.4%)	**91**
Canadian University	62 (62.6%)	37 (37.4%)	**99**
Total	**129 (67.9%)**	**61 (32.1%)**	**190***

Note: * two students did not indicate their working experience.

Table 3: The number of participating students in each institution and gender category

Institution	Gender?		**Total**
	Male	Female	
UK University	76 (85.4%)	13 (14.6%)	**89**
Canadian University	33 (34.7%)	62 (65.3%)	**95**
Total	**109 (59.2%)**	**75 (40.8%)**	**184***

Note: * eight students did not indicate their gender.

Table 4: The number of participating students in each institution and implementation phase category

Institution	Implementation phase?		**Total**
	Phase 1	Phase 2	
UK University	45 (48.9%)	47 (51.1%)	**92**
Canadian University	52 (52.0%)	48 (48.0%)	**100**
Total	**97 (50.5%)**	**95 (49.5%)**	**192**

Table 5 presents significant relationships between (institution, gender, working experience, implementation phase) categories and collaboration variables. The analysis revealed some evidence of relationships between 'institution' category and two perceptions of distance collaboration, namely (i) 'In group work, I am exposed to higher risk of a poor mark (V3)' (p=0.051), and (ii) 'Face-to-face (offline) meeting essential for high performing team (V10)' (p=0.003). Further evaluation of the data indicates that Canadian students were more likely to feel that group work would not expose them to higher risk. However, they were likely to believe that face-to-face (offline) meeting was essential to achieve higher team performance.

Significant relationships were found between 'In group work, I am exposed to higher risk of poor mark (V3)', and both 'gender' (p=0.014) and 'working experience' (p=0.039) categories. An observation of the data suggests that female students and those who have previous working experience would tend to disagree that group work brings higher risk. Furthermore, there was a significant relationship between 'working experience' and 'communication over the internet is difficult (V9)' (p=0.008). Examination of the responses indicates that those who have previous working experience tended to disagree to the statement that communication over the internet is difficult.

An evaluation of the relationships between implementation phase (pre-implementation in semester 1 and post-implementation in semester 2) and collaboration variables revealed that the students tended to agree that ‘face–to-face meeting is essential for high performing team (V10)’ in semester 2 (p=0.023). Perhaps, by the end of design project, the students feel that the issues encountered could have been better resolved through offline face-to-face meetings, if there is any means to organise this. However, the number of the students who disagreed with the statement ‘I need the other team to complete my work (V15)’ was significantly less in the post-implementation survey (p=0.002). Following their participation in the design project, a proportion of the students surveyed may have come to realise the need to work in team to undertake their work. This may be viewed as a positive improvement in the attitude to collaboration, and the project may have contributed to their enhanced appreciation of inter-dependencies between parties in the design process.

The analysis of VARK data suggests that there is tendency for different communication modes used by the two professions, with architects preferring visual and kinesthetic modes, and civil/structural engineers preferring the read/write mode. This difference was significant in year 1 (p = 0.014) and overall combined responses (p = 0.018) (see Figure 1). However, this difference was not significant in year 2. An analysis based on gender categories revealed a similar tendency with females preferring visual and kinesthetic modes, and males preferring the read/write mode (year1, p = 0.067; overall, p = 0.069). This may be because the majority of architectural students in the Canadian university were female, and the majority of civil/structural engineering students in the UK university were male (see Table 3). There is no relationship between both working experience and implementation phase, and VARK categories in the first, second and combined years.

Table 5: Significant relationships between categories and other variables

Category versus Variable	Probability value
Institution vs. “In group work, I am exposed to a higher risk of a poor mark” (V3)	0.051
Institution vs. “Face –to-face meeting is essential for high performing team” (V10)	0.003
Gender vs. “In group work, I am exposed to a higher risk of a poor mark” (V3)	0.014
Working experience vs. “In group work, I am exposed to a higher risk of a poor mark” (V3)	0.039
Working experience vs. “Communication over the internet is difficult” (V9)	0.008
Phase vs. “Face–to-face meeting is essential for high performing team” (V10)	0.023
Phase vs. “I need the other team to complete my work” (V15)	0.002
Institution vs. VARK (year 1)	0.014
Institution vs. VARK (year 2)	0.705
Institution vs. VARK (years 1 and 2 combined)	0.018
Gender vs. VARK (year 1)	0.067
Gender vs. VARK (year 2)	0.531
Gender vs. VARK (years 1 and 2 combined)	0.069

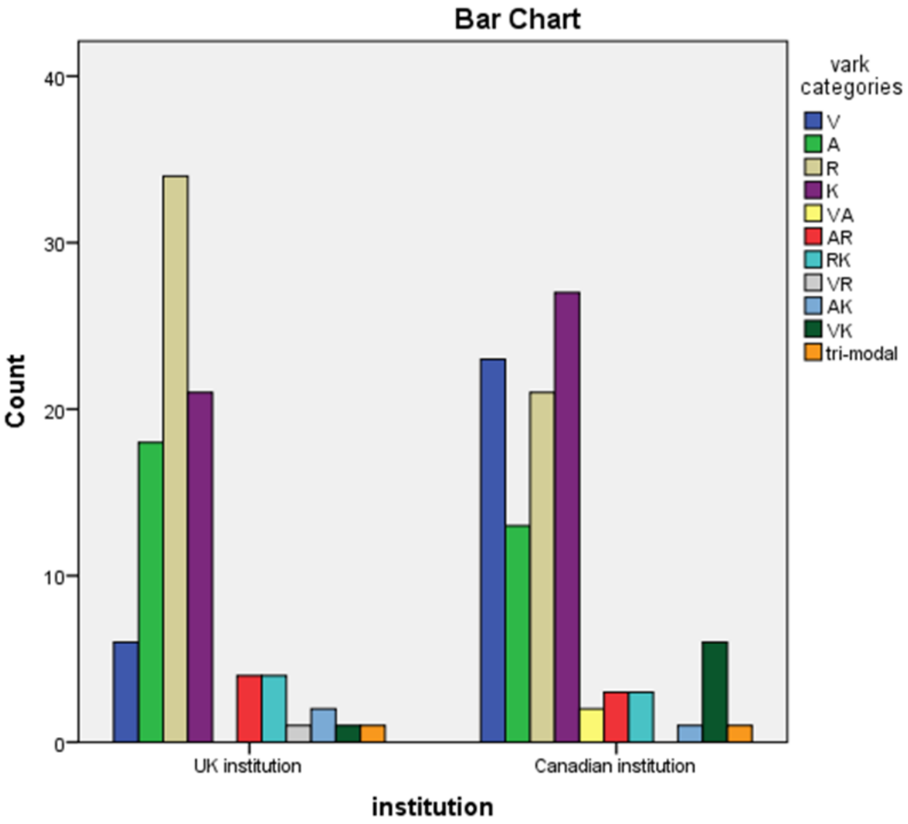

Figure 1. VARK profile for institutions (years 1 and 2 combined)

DISCUSSION

The findings highlight the significance of perceived risk, face-to-face meetings, internet communication, and perceived dependency on one another. Particularly, it is worth noting that the perception of risk was found to be significantly different in three categories, namely institutions/ disciplines, gender, and work experience. When an individual is going to undertake a particular task, in their mind they consider the personal risk and reward from undertaking the task. The perceived risk and reward also influences the level of trust between members in a virtual team (Zolin *et al*., 2004). This perception determines their behaviour and commitment, and ultimately the performance of a virtual team. Architecture students in the Canadian university perceive less risk in group work than their civil/structural engineering students do in the UK university. The same finding was found with female students who represent the majority of architecture students, and those who have previous working experience. Architecture students also perceive a need for face-to-face meetings, more so than their counterparts. An explanation for this may be found in the fact that architecture students are required to spend more of their time working with their colleagues in the design studio, which familiarises them with group learning and a higher level of face-to-face interactions. The process facilitates the development of trust, hence the perceived lower risk associated with group work. Those with previous working experience might tend to realise the need for group work and communication over the internet to deliver their projects, and therefore this mode of working is often not just necessary, but essential for collaboration.

The difference in the preferred communication modes used by the two professions raises an important question; to what extent has this difference been formed by disciplinary training? To address this question, a comparison of the preferred communication modes of the general population can provide a reference from which an inference may be drawn. The VARK website, which has been online since 2001, can provide a comparison with the general student population. Based on online responses from around 80,000 students from different levels (including universities, colleges and high schools), Fleming (2015) found significant differences between males and females in their preferred communication modes with men having more kinaesthetic responses and women more read/write responses. Similar to the finding of this research, he also found that subject discipline can influence VARK preferences with those studying graphic design and art subjects preferring visual modes of communication. If the responses in this research demonstrate the same tendency, the finding suggests that training in subject disciplines can influence students' preferred communication mode.

The findings from the quantitative data analysis point towards the need to address perceived risk of distance collaboration in virtual teams, and to raise awareness of different preferred communication modes between members from different disciplines. The perceived risk may be lowered if the members have experienced a virtual teamwork process in their previous work assignment. If they have not had this experience, familiarisation with the virtual teamwork process before they embark on the assignment could also be beneficial. In the group learning setting, the tutor could facilitate familiarisation by providing guidance throughout the duration of the project, and if necessary act as the mediator to resolve any relationship issues/ conflicts which are beyond the means of the learning groups. The mediator was found to be an important factor to enable effective process of virtual collaborative learning (Soetanto *et al*., 2014). However, it is important that tutors should, as far as possible, let students resolve issues by themselves, because experiencing group dynamics, and managing content and relational space (Leinonen *et al*., 2005) are an integral part of learning in the virtual team. It is also important to appreciate different ways of communicating design information. Sketches, drawings and 3D digital models may be used as media for communication; however they may not be able to support the breadth of activities in collaborative interaction in a virtual design team. For example, Dossick and Neff (2011) suggested that current building information modelling (BIM) technologies do not fully support knowledge synthesis during collaborative interaction as they appear to be fixed and immutable. They argued the need for active, informal and flexible media to support joint problem solving in the virtual team. Notwithstanding media requirements, this seems to suggest that the use of multiple communication modes (e.g. discussion in online meetings, exchange of emails, 3D BIM models) may benefit collaborative interaction in the virtual team. Similarly, Dossick *et al*. (2015) identified a gap of knowledge in the distributed design work of the virtual team and how to best support the virtual teams. The following section presents guidance to support international collaborative design projects, which aims to help to lower the perceived risk of collaboration in virtual teams.

GUIDANCE FOR IMPLEMENTING COLLABORATIVE DESIGN PROJECTS

There is very little evidence that guidance for implementing a collaborative design project exists. Several scholars have published lessons learnt from their implementation in their classes, but these are somewhat piecemeal and do not cover activities comprehensively. This is mainly due to the variability of implementation (Solnosky *et al*., 2014). One recent example, Lee *et al*. (2013) provides guidelines for integration of BIM in construction engineering and management education. It includes technical and management skills which could be introduced by integrating BIM in the curricula. However, it does not fully cover detailed operational aspects of collaborative design project implementation. It also does not provide practical guidance on the 'act of collaboration' in an online environment.

The guidance below was developed mainly for BE educators who are contemplating, or about to implement, collaborative building design project within their programmes of study, involving international partner(s). The guidance not only provides practical advice to implement a collaborative design project based on the experience of the research team, but also good practice in collaborating online, which were synthesised from the data collected during a course of one academic year.

The aim of the guidance is to help BE educators and learners to develop strategies to achieve a high level of collaboration awareness, and hence to enable effective online collaborations. The strategies were structured in several themes arranged in a hierarchical order, where one theme provides support for the level above it. This hierarchy is diagrammatically presented in a pyramidal model, divided with horizontal slices which each represented each theme. The pyramidal model is shown in Figure 2. The model and complete set of guidance can be seen in http://bim-hub.lboro.ac.uk/. It is not intended to be comprehensive or directive, rather to articulate a set of guiding principles, which can be used in the design and implementation of students' learning activities.

Level 1: Satisfying institutional requirements and aligning with professional guidelines

Level 1 focusses on institutional and professional considerations for facilitating the implementation of an international collaborative design project. It comprises considerations of implementing institution and professional body requirements on the programme/course. It advises on required adjustments to the existing institutional embedded practice and challenges of these adjustments might encounter. It also covers details of various operational aspects, including choosing collaboration and educational technologies, prior skills of participating students, organisation of consultative meeting between tutors and students. Level 1 sets up the ground rules for the activities, considering the context in which it is to be implemented.

Level 2: Designing activities for online collaborative design

Level 2 discusses how to run a collaborative design project across multiple institutions, and to develop the design brief, learning and peer assessment requirements which are consistent and fair for all participating students. Levels 1 and 2 may vary according to subject disciplines, but this has been compiled specifically for BE subjects. The remaining levels relate to generic skills that apply to any collaborative design activity that students may undertake.

Level 3: Support for collaboration

Levels 3 and 4 will be relevant for any collaborative project, whether offline or online. Level 3 looks mainly at the support needed by students when engaged in collaborative activities as part of the curriculum. It is assumed in this case that teams from more than one university are studying different modules (each at their own university), but have a collaborative exercise as part of those modules. This level underlines the need to support the students to maintain good communication throughout the project. It also touches on the use of compatible software.

Level 4: Skills for collaboration

Level 4 looks at the skills that students need to acquire to conduct collaborative activities effectively, whether offline or online. The question of how many of these to directly address with students, and how many are best left for them to learn by experience remains open. It is suggested to raise them as 'things to be aware of', then observe students to see if failing to acquire them is particularly impeding their ability to conduct the activity, at which point some remedial additional seminars on the skills could be implemented. These skills are, in general, applicable to any subject discipline. They are also applicable to collaborations that are intra-organisational (although inter-disciplinary) only. Inter-organisational and international collaborative skills are addressed in the online section, since inter-organisational and international collaborations are likely to be conducted online.

Figure 2. Pyramidal model of guidance for an effective online collaborative design project

Level 5: Platforms for collaboration

Levels 5 and 6 refer specifically to projects that take place online, when teams are working collaboratively in a virtual environment. This is also the point at which many of the skills of working on inter-organisational and international collaborations can be acquired. Level 5 records the use of technologies by participating students and requirements of hardware and software to enable collaboration. In the project reported here, students were free to use any platforms they wished for their asynchronous working, but were assigned GoToMeeting for their synchronous meetings. All students used email for lengthier communications, most used Dropbox for sharing and storing information, and all used Facebook for communication that required a faster response. The skills they acquired to use the technologies are covered in sections 6 and 7.

Level 6: Skills for online collaboration

Level 6 looks at the skills the students learnt to apply when moving to an online environment. Many of these appear to be generic skills that would need to be used in any collaborative activity. However, it emerged that the students, although all had worked in teams before, had not acquired these skills. None had experience of virtual teamwork before beginning the project. This was because of the degree of contact they had with other members of their teams when working face-to-face. This meant that these previous collaborations could be affected easily on an *ad hoc* basis. It therefore needs to be noted that, even if the students are familiar with offline collaboration, some skills will need to be acquired when they move to an online environment. Also in reality, most of the challenges that come with inter-institutional and international collaboration are introduced at this point, as the face-to-face collaborations the students were exposed to will be intra-organisational only.

Level 7: Skills for synchronous collaboration

The skills needed for successful synchronous online collaboration are additional to those, which are routinely used in offline team-working. Level 7 is specifically for these additional skills required when activities take place synchronously, usually during videoconferencing. Some skills appropriate only to international collaboration can also be acquired here. In the project reported in this paper, students used GoToMeeting, but the skills considered here are independent of the platform used. Guidance at level 7 focuses on making the students aware of the basic norms of behaviour that can be adopted in online meetings. Some of the skills may be seem at first to be self-evident, but in the project, the students were often unaware that they needed them at the start of the collaborative process and sometimes failed to acquire them by the end. Whether the tutors choose to instruct students at the start, or allow them to discover the skills for themselves through trial and error, is a matter of judgment. To be effective, learning from experience requires opportunities for reflection, which can be time-consuming. Consequently, those working on a short timescale may need to fast-track the learning process using the guidance materials we have provided.

However, some of these behaviours should be regarded as essential as they are necessary to meet inclusivity and equality protocols of institutions, and it is appropriate to inform students that they must be used when interacting with each other. As the students became familiar with the use of the GoToMeeting platform, several changes in behaviour became apparent, e.g. they adopted better meeting management techniques, they became more fluent in using the technology for their own purposes, their interactions with each other were faster and clearer and they presented a more positive online presence. In part this was because tasks and roles become clearer as a project progresses, but in part this was because the students became more experienced with how to conduct themselves online and confident at working in a virtual environment.

CONCLUSION

The application of a collaborative design project in the BE curricula is not new. However, the approaches, object of design, supporting technology used, location, discipline composition and training of participants in the implementation of this activity in the BE curricula vary considerably. Consequently, the outcomes and impacts are difficult to replicate outside the context where it was evaluated. A review of literature suggests that relatively little is known about the elements that determine and influence virtual team performance (Lee-Kelley & Sankey, 2008; Algesheimer *et al.*, 2011). This has led to the need for a greater understanding of factors influencing multi-disciplinary virtual team interaction and collaboration (i.e. risk, trust, learning style). Furthermore, previous implementations have not provided sufficiently comprehensive lessons learnt, and therefore, meaningful guidance on how to implement multi-disciplinary and –institution international collaborative design projects is arguably absent. To address this gap in knowledge, the paper presents the key findings from a three-year international collaborative design project implementation in UK and Canadian universities, including the analysis of primary data on the perception of collaboration and preferred communication modes, and the guidance for effective practice in an international collaborative design project. The main target audience for the guidance is BE educators who are contemplating, or about to implement, a design project within their curricula, involving international partners. However, those participating in online collaboration can also benefit.

The findings show the effect of disciplinary training on the perceived risk of collaboration and preferred communication mode. Familiarity with team-based collaboration and studio-based learning where frequency of in-person meetings is high, might have facilitated the development of trust between colleagues, and reduced perceived risk. Higher perceived risk is not conducive to successful collaboration as individual members can decide to take actions to protect their own interest and be only partially committed to group work. Consequently, the benefit of co-creation of design, which can provide an optimum solution to the problem, cannot be obtained. In the context of group learning, tutors should consider mechanisms and activities to reduce the perceived risk of collaboration by, for example, providing guidance, taking on a mediating role (if there is a need for intervention), encouraging social gatherings, or the use of social media (if face-to-face meetings are impossible). This informal communication can help the development of trust (Strahorn *et al*., 2015) and benefit knowledge synthesis in joint problem solving (Dossick & Neff, 2011). Following their participation in the design project, the students realised a higher perceived dependency on others in undertaking their work. This suggests a positive impact on their attitude to collaboration.

Assuming that the findings of Fleming (2015) are valid and represent the population of those in education, our findings suggest that training in the subject discipline can influence the preferred communication mode of individuals. It is worth noting that a mismatch of preferred communication mode amongst individual members from different disciplines can lead to inaccuracy of information exchanged, ineffective and inefficient process, and hence sub-optimum design solutions. In the worst case, mismatch causes conflicts between members of project team (Fleming, 2015). This highlights the need to raise awareness of different preferred communication mode between members of different disciplines. Given the challenge involved in the process of knowledge synthesis, the use of multiple communication modes (e.g. discussion in online meetings, exchange of emails, 3D BIM models) may benefit joint problem-solving in a virtual team. While it may be unreasonable to expect that members of project team should have the same tendency for certain communication modes, this finding reiterates the need for integration between BE disciplines, which is an important message for stakeholders in BE education. In practical terms, BE students should be exposed to subjects beyond traditional disciplines, giving them a wider and richer range of skills required to work in the 21st century. These skills will enhance their appreciation and understanding of the requirements of built facilities beyond their disciplines. In the long term, this process will help to dismantle the ‘disciplinary silos’ which have hampered the performance of industry for centuries. For other stakeholders in the BE sector, the findings of this research suggest the need to reduce perceived risk in virtual collaboration and to use multiple modes for communication of complex information in design and construction process. The perceived risk may be reduced by better understanding of the collaboration process, and by having an early consensus on planned activities involved. To reduce the perceived risk, trust between team members is essential.

Several limitations and the need for further research are detailed as follows:

- Although the overall findings were found to be significant, there were discrepancies in the findings between the first year (as presented in Soetanto *et al*., 2012a; 2012b) and the second year of implementation (see Table 5, non-significant findings of VARK preferences). This inconsistency suggests the need for further data collection to develop a more complete pattern of VARK preferences.
- The findings on preferred communication modes suggest the need for further research to explore the optimum utilisation and combination of communication modes to achieve knowledge synthesis in the virtual collaborative building design.
- The guidance presented in this paper serves as a means to share the authors’ experience to help BE educators and enhance their practice. It should be trialed in different contexts and further developed based on the evaluation of the outcomes.
- Using students as participants brought several advantages, notably higher response rates to the data collection exercises and importantly, higher degree of control over the tasks required in this ‘experiment’ (in terms of e.g. comparability across the groups). Although the use of students as respondents aligns well with the research focus on early education of BE professionals, a generalisation to industry professionals should be drawn with caution, as they would have acquired more experience and other influences in the workplace.

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REVIEW OF THE POTENTIAL FOR A CYBER-PHYSICAL SYSTEM APPROACH TO TEMPORARY STRUCTURES MONITORING

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Abstract

Around three quarters of construction workers work on or near temporary structures, whose failures lead to more than 100 deaths, 4500 injuries, and damage costing $90 million each year in the United States. However, few of the temporary structural problems have been well addressed, especially when compared with the increasing improvements in permanent structures. Meanwhile, the review of leading causes of temporary structural failures identifies the need for improved methods, such as Cyber-Physical Systems (CPS), to prevent potential structural hazards. This paper makes the first effort to examine CPS applicability in temporary structures, and potential benefits brought by CPS to temporary structural monitoring. Key definitions and features of CPS, CPS applications in both other industry sectors and the built environment, and applications of CPS enabling technologies in temporary structures are reviewed. It is concluded that CPS provides opportunity to address safety and structural problems of temporary structures. For a clear understanding of how CPS works in structural monitoring, an application scenario of scaffolding system is presented. Finally, system requirements followed by a system architecture are identified.

Keywords: *Cyber-Physical Systems, temporary structural monitoring, system architecture*

INTRODUCTION

The construction industry has had a long-standing record of poor productivity (Park et al. 2005), safety hazards (Mohamed 2002), financial waste (Shane et al. 2009), and schedule delays (Shi et al. 2001). Some of these problems, like occupational injuries, quality of structure, and speed of construction project, are affected by temporary structures (i.e. scaffolding, temporary support system, and formwork system) (Fabiano et al. 2008). To be specific, it is estimated that three quarters of the construction workers in the United States work on or near temporary structures (OSHA 2014). The improper management of temporary structures results in 100 deaths, 4500 injuries, and costs $90 million every year (BLS 2013).

The term 'temporary structures' refers to systems and assemblies used for temporary support or bracing of permanent work during construction, and structures built for temporary use. The former are defined as the elements of civil engineering work, which support or enable the permanent works (Grant and Pallett 2012). Included are temporary support systems such as earthwork sheeting and shoring, temporary bracing, soil backfill for underground walls, formwork systems, scaffolding, and underpinning of foundations. The second category includes temporary or emergency shelters, public art projects, lateral earth retaining structures in construction zones, construction access barriers, temporary grandstands and bleachers, and indoor and outdoor theatrical stages (Parfitt 2009).

The last four decades have seen numerous collapses related to improper erection and monitoring of temporary structures. In 1973, the improper removal of forms triggered a progressive collapse of the Skyline Plaza (Bailey's Crossroads, VA), killing 14 construction workers and injuring 34 others (Feld and Carper 1997). Another example was the collapse of a section of the University of Washington football stadium expansion in 1987 due to premature removal of temporary guy wires (Feld and Carper 1997). A major scaffold system on a 49-story building on 43rd street in New York's Time Square collapsed in 1998 as a result of bracing removal, resulting in the death of one individual, several injuries and hundreds displaced from their residences (Stewart 2010).

Considerable efforts have been made to prevent temporary structural failures, including safety regulations on the design, installation, maintenance, and dismantling of temporary structures, safety training programs required by government, and case studies of serious temporary structural failures. However, there are still some temporary structures, such as indoor and outdoor theatrical stages, which are not covered by any safety regulations (Mckiniley 2011). Besides, even with enough safety regulations and training programs, the temporary structural failures cannot be fully prevented as the workers tend to work under great pressure and make mistakes unconsciously (Fabiano, et al. 2008). For automatic and continuous monitoring of temporary structural integrity regardless of causations, an intelligent temporary structural monitoring system, which can track and monitor the temporary structural performance, is in high demand (Jung 2014).

Recent developments in information and communication technologies, such as data acquisition system (DAQ), Building Information Modeling (BIM) and CPS applications in improved structural health monitoring, provide the potential for improved temporary structures monitoring. The use of CPS offers an opportunity for changes in the physical structure to be captured and reflected in a virtual model. Conversely, changes in the virtual model can be communicated to DAQ embedded or attached to the physical components. This bi-directional coordination between physical and virtual systems enables the temporary structures to be continuously monitored and assessed for performance in order that potential hazards can be identified and addressed prior to an accident, irrespective of causation.

This paper proposes and analyzes the potential for a CPS approach to temporary structures monitoring. First, the key definitions and features of CPS are summarized for a better understanding and its potential benefits. Second, CPS applications in other industry sectors and in the built environment are reviewed to identify current research limitations and explore CPS applicability in temporary structures. Third, potential areas for CPS applications in temporary structures are identified, including both temporary performance stages and temporary support systems. According to previous analyses, the potential benefits and barriers, as well as an application scenario in temporary structures monitoring are presented. Finally, based on the identification of system requirements, the system architecture is designed as an example for CPS approach to temporary structures monitoring.

RESEARCH METHODOLOGY

This paper presents the findings of the on-going applications of CPS in various industry sectors, and the critical issues to be addressed for temporary structures with an aim to identify CPS applicability to temporary structures. Due to the objectives, the research methodologies adopted for this study include literature review, scenario development and validation, and expert interview. The literature review was conducted to identify the potential opportunities, approaches and benefits offered by CPS to temporary structures, and the system requirements. The urgent need for enhanced management of temporary structures is also reviewed. An application scenario to temporary structures was developed and validated as an example of how the temporary structures may be better monitored. Finally, the expert interview was conducted to validate the identified system requirements, which assists in the system architecture design of CPS for temporary structures monitoring.

OVERVIEW OF CPS

Due to their different research scopes, researchers view CPS in different ways. A better understanding of its definition and key features is helpful in the identification of potential benefits and barriers to CPS application in temporary structures.

Key definitions of CPS

Several researchers have defined CPS as follows:

• Cyber-Physical Systems are smart systems that have cyber technologies, both hardware and software, deeply embedded in and interacting with physical components (Smart System 2012). This definition regards CPS as an integration of both software and hardware, where the physical and virtual components can interact with each other through embedded instruments.

• Cyber-Physical Systems are physical and engineered systems whose operations are monitored, coordinated, controlled and integrated by a computing and communication core (Rajkumar et al. 2010). From this perspective, the focus of CPS is more about the control and communication of the physical system through the computing system. It highlights the function of remote control and monitoring of the real world by CPS.

• Cyber-Physical Systems are integrations of computation with physical processes, wherein networked embedded computers monitor and/or control physical processes based upon local (i.e. in-network) and remote (i.e. back-end) computational models (Krogh et al. 2008). Based on this definition, it can be concluded that CPS enables the computing system to control the physical system through a network.

• Cyber-Physical Systems are large-scale interconnected systems of heterogeneous components that are envisioned to provide integration of computation with physical processes (Lee 2007). Therefore, CPS provide a solution to integrate several heterogeneous components, so that the physical world can be well controlled by the computing system with different functions based on the users' purpose.

In general, CPS are used as an interaction system where the physical world and virtual world can communicate and interact with each other seamlessly. Considering for the purposes of this paper, a CPS is simply considered as the effective bidirectional integration of computation with physical processes. Embedded computers and networks monitor and control the physical processes with feedback loops, where physical processes affect computations and vice versa (Derler et al. 2012).

Key features of CPS

By definition identified above, a CPS involves a high degree of integration between computing (virtual) and physical systems (Greenwood et al. 2015). Distributed applications are also common which involve distributed management and/ or distributed operations such as a power grid. Another feature of CPS is the ability to provide timely service in the face of real-time constraints (Wan and Alagar 2012).

In general, the key features of CPS can be summarized as integration, distributed system, real-time system, virtualization, adaptability, automation, heterogeneity, and uncertainty (Table 1). By integration, the CPS combines the physical and computing system through mutual information exchange and control, instead of only tracking the physical world with a computing system or vice versa (Wu and Li 2011). Besides, CPS provides distributed management for it can be a large system consisting of several distributed systems. In this way, by using CPS, multiple parties can remotely obtain access to the project from different places for project management or cooperation. Meanwhile, CPS is capable of real-time communication, which enables continuous integration and up-to-date information exchange between the virtual and physical systems. The integration between virtual and physical systems can be updated in real time. In terms of virtualization, CPS creates a virtualized interface for users to remotely analyze and track the physical system. It also enables all the physical components to be identified and recognized accurately in the virtual model (Penna et al. 2010). The feature of adaptability means that CPS is capable of adapting to changing situations through dynamic reorganizing /reconfiguration (Khaitan and McCalley, 2014). The automation feature enables the automatic control of physical system according to continuous tracking. During the automatic control process, actuators are triggered based on system analysis and command. From the perspective of heterogeneity, CPS integrate several different systems together with standard communication and information exchange. It also integrates various devices, including sensors, mobile devices, high-end workstations and servers (Wan et al. 2011).

Overall, CPS integrates the physical structure and its corresponding cyber systems seamlessly at all scales and levels. Automatic and resilient human-machine interaction is supported by CPS for improved control, efficiency and reliability of the physical systems (Lee et al. 2015).

Table 1: Key Features of CPS

Researcher	Integration	Distributed	Real-time	Virtual	Adaptability	Automation	Heterogeneity
Wu and li (2011)	Combination; networked						
Shi et al. (2011)	Integrated networked			cyber capability in physic world	adaptive	highly automation	complex
Anumba et al. (2010)	interaction	tagging and tracking physics		virtual			
Wan and Alagar (2012)	sharing resource	distributed system; Geographically distributed	real-time				heterogeneity
Wan et al. (2011)	couple with physics						heterogeneity
Geisberger et al. (2011)	networked;	distributed control; systems of system			adaptive	partial autonomy; human-machine cooperation	

CPS APPLICATIONS

In exploring CPS applicability in temporary structures, it is important to understand its applications in other industry sectors where CPS has been adopted and developed for advanced management. In addition, a review of current CPS applications in the realm of the built environment could help to identify the current research gaps, examine CPS applicability, as well as to identify potential application areas in temporary structures monitoring.

CPS applications in other industries

CPS was initially developed in other industries such as manufacturing industry, power grid, transportation industry, and healthcare industry. Some of the applications in these industry sectors are briefly reviewed in this section.

Manufacturing industry

Smart manufacturing refers to the manufacturing industry which, with the application of CPS for the tracking and monitoring of a product throughout its life cycle, can optimize its performance and efficiency (Coalition 2011). Current manufacturing resource aggregation (MRA) cannot adapt to dynamic factors, which greatly impact the quality and efficiency of the manufacturing industry. In viewing this problem, Liu and Su (2011) pointed out that CPS can provide real-time information on physical resources and thus support the realization of dynamic MRA. Liu and Su's study gives a new solution for dynamic MRA with the aid of CPS. Taking advantage of the real-time feature of CPS, Kaihara and Yao (2012) developed a Real-Virtual Integrated Scheduling System based on the concept that CPS is the combination of the computational and physical worlds (Lee 2007). Their developed system helps to manage dynamic changes at production sites through the dynamic scheduling of the real system and simulation of the virtual system.

The main challenges for CPS the implementation in manufacturing industry include network integration, affordability, and the interoperability of engineering systems (Aderson 2011). The use of CPS in manufacturing industry requires seamless connection between each node. While the manufacturing industry's network has enabled the life-cycle management of products, the implementation of CPS requires high-speed, stable, and seamless communication for real-time inspection and control. Therefore, more integrated network should be set up before CPS can be fully implemented in this area. Due to the high cost of both retrofitting existing control system and the initial set up of CPS, there is no motivation for small and medium-sized companies to investigate CPS. Besides, most of the manufacturers use different kinds of engineering systems for production management, and even customize their own software and system. The lack of an information exchange standard regulating the data type of the manufacturing files from various manufacturers prohibits the quick promotion of CPS, for CPS has to be adjusted and re-designed for each manufacturing company due to the lack of interoperability of engineering systems (Smart Systems 2012).

Power grid

The smart grid is a complex ecosystem of heterogeneous (cooperating) entities that interact to provide the envisioned functionality (Karnouskos 2011). In view of the fact that the infrastructure for both the electric grid and water distribution systems is aging with technical and reliability problems, Krogh et al. (2008) proposed that the electric grid and other utilities can use CPS technologies for a smarter and more efficient system. CPS is valued as an integral part of smart grid (Karnouskos 2011). To verify the correctness of cyber-physical composition, Sun et al. (2007) introduced a model to avoid interference among components of a system. Furthermore, since CPS imposes increasing uncertainties on controlled systems, Zhu and Basa (2011) proposed a holistic theoretical framework and applied it to power systems. This framework helps to maintain an appropriate level of CPS operation even during unexpected system interruptions.

With CPS implementations in smart power grids, challenges to be dealt with include system security, data analysis, and the integration of new technologies. The system security requires that the system should not easily crash even when there is a high consumption demand, or when the system is attacked. Besides, while the use of CPS enables multiparty access to the power grid management system to get or provide energy to the system, such distributed accesses to the smart power grid impose the risk of hacker attacks. Because the power grid produces large amounts of data for analysis, an appropriate data fusion method is critical to CPS for automatic control of the power grid system. Besides, the integration of CPS with current power grid management system calls for great efforts in analyzing existing system, a proper way of adding CPS to existing power grid management system, as well as the use of new technologies for enhanced functions with use of CPS, such as energy storage technologies (Baheti and Gill 2011).

Transportation industry

Recent traffic problems, such as traffic jams and accidents, call for the improvement of transportation system (Ge et al. 2004; Gong and Li 2013). CPS offers the potential to an intelligent traffic system through real time detection of system status, optimal route plan, and adjustment of control strategies (Gong and Li 2013); and is valued as the promising approach to aerospace education, research, training, and accelerated workforce development (Noor 2011), and the transformation of the national airspace system (NITRD 2012). Four research areas, including (1) new functionality, such as higher capacity, greater safety, more efficiency; (2) integrated flight deck system for (semi)autonomous system; (3) vehicle health monitoring and management; (4) safety security of aircraft control system, have been identified for CPS applications to the future air transportation system (Baheti and Gill 2011). Mertins et al. (2012) also proposed a CPS application to aircraft maintenance repair and overhaul, with the aim to simplify and shorten the execution of Maintenance, Repair and Overhaul (MRO)-Processes which impact aircraft availability. To facilitate the application of CPS in the transportation domain, a low-priced intelligent vehicle with wireless sensor networks navigation, was designed (Wan et al. 2011). Furthermore, based on CPS theory, Gong and Li (2013) proposed a fusion framework for urban traffic control system, which aims to avoid traffic congestion and improve traffic efficiency. This study provides a theoretical foundation for CPS implementation in intelligent traffic system.

Safety and security, which are most important to the transportation industry, remain big challenges before CPS can be fully adopted (Smart System 2012). The safety threat means that the use of CPS may distract the attention of drivers and result in a higher risk of accidents. Besides, the safety of transportation systems is also highly impacted by system security when there are system logic problems of unmanned vehicles, system interruptions, and hacker attacks (NITRD 2012). All of these concerns call for a high confident CPS to be used for transportation management (Lintelman et al. 2008).

Healthcare industry

Healthcare increasingly relies on networked medical systems to take care of patients with special circumstances. An example is the use of sensors to track the conditions of patients during operations. However, these techniques should be assembled into a new system configuration, such as CPS, to match specific patient or procedural needs (Baheti and Gill 2011). It is envisioned that the next generation of healthcare systems would be secure and reliable systems with wired and wireless networked medical devices (Arney et al. 2010) and medical information systems (Sha et al. 2009). The application of CPS in healthcare involves the national health information network, electronic patient record initiative, home care, operating room, etc. (Shi et al. 2011). Lee and Sokolsky (2010) discussed current trends and promising research directions in the development and use of high-confidence medical CPS. To cope with the safety issues, Cheng (2008) proposed a method to allow the safe cyber-physical operation of a medical ventilator, a life-critical reactive device, to move breathable air into and out of the lungs of a patient with respiratory difficulties. This study also examined potential research areas so that the safety operation of CPS application in healthcare industry can be improved.

Several challenges for CPS application in healthcare industry remain to be tackled. For example, the complex relationship between a patient's health condition and the required medical condition calls for an accurate algorithm with several parameters other than the time (Cheng 2008). In viewing the trend of medical CPS, Lee and Sokolsky (2010) identified the challenges raised by CPS, including safety of patients, collaboration and interoperability between several treatment systems to one patient at the same time, a simple patient model covering all needed information and a comprehensive simulation for test and validation, adaptive patient-specific algorithms with special concerns to unique parameters to a certain patient, and open interconnectivity standards for medical CPS.

CPS applications in the built environment

The construction industry is in need of continuous improvement in areas such as intelligent safety management, cost and resource management, scheduling, and energy conservation. With development in information technologies, recent research (discussed below) have recognized the potential benefits of CPS to the built environment from various perspectives, including: project delivery process, automatic construction site layout generation, construction progress monitoring, light fixture monitoring and control, and Structural Health Monitoring (SHM). Current CPS applications demonstrate how the built environment could benefit from CPS.

Project delivery process

Current project delivery processes are inefficient and there is a need of transformation so that greater control can be made through an integrated system. By identifying the limitations of previous efforts on managing the construction process, Anumba et al. (2010) demonstrated the need for CPS to improve the project delivery process, and proposed a CPS approach targeting the integration of virtual models and the physical world through a bi-directional flow of information. This provides reference for future research efforts in this research field. Akanmu (2012) highlighted the mechanism and triggers for the bi-directional flow of information. Through use-case scenarios validation and expert interviews, CPS applicability was demonstrated in enhancing bi-directional coordination between virtual models and the physical construction world.

Automatic construction site layout generation

In view of the importance of resource layout and activities to the success of construction projects, Akanmu et al. (2015) proposed the use of CPS for construction site layout and developed an automated component level system for optimized and real time site layout. Case studies demonstrated that the developed system provides an effective means for real time construction site space tracking and the automatic generation of construction site layout.

Construction progress monitoring

Potential benefits of CPS to construction progress monitoring were highlighted by Olatunji and Akanmu (2015) with the development of an adaptive CPS approach for construction progress monitoring and control. Besides, Yang et al. (2015) proposed the use of vision-based method for construction performance monitoring, including the control of construction progress both at the project level (civil infrastructures and elements) and the operation level (construction equipment and workers).

Light fixture monitoring and control

Building on the previous studies, Akanmu presented an approach to improve light fixture monitoring through CPS integration between virtual models and physical light fixtures. A prototype system was developed and implemented for tracking, monitoring and controlling light fixtures throughout a facility life cycle (Akanmu et al. 2014). Other possible applications were also identified, such as management of urban infrastructure street lights, mechanical systems and other building components such as window blinds, etc.

Structural Health Monitoring (SHM)

SHM helps to prevent civil structural failure or costs by providing information and assisting in decision making for preventative measurements (Smart System 2012). To improve the evaluation of structural performance, recent research has applied CPS to SHM by integrating the computing elements and structural components. According to Hackmann et al. (2014), SHM represents an important application domain of CPS. To integrate damage detection and energy saving, they proposed a cyber-physical co-design approach to structural health monitoring using wireless sensor networks. This approach can selectively activate nodes in the damaged region so that local damage is detected while allowing the rest of the nodes to remain asleep. Tidwell et al. (2009) pointed out the main challenges of CPS application to SHM, such as the actuator dynamics, complex interactions between physical components and their virtual models, and the computation and communication delays. To improve the hybrid real time testing, Tidwell et al. (2009) provided a highly configurable and reusable middleware framework for real-time hybrid testing. This study improves the high-fidelity real-time testing and promotes CPS applications in this area.

As shown in the previous sections, previous researchers have explored CPS applications and potential benefits in a variety of areas of the built environment. CPS has been identified as being applicable to various aspects of the construction industry by integrating and coordinating virtual and physical construction systems. However, CPS applications in the built environment are still limited to the project delivery process, construction site layout generation, construction progress monitoring, light fixture monitoring, and structural health monitoring of critical infrastructures. Few efforts have been made to take the benefits of CPS to temporary structures, whose performance may have great impacts on construction quality and workers' safety. Various applications of CPS enabling technologies (discussed in the following section) have been implemented for enhanced monitoring of temporary structures, which indicates CPS applicability and potential benefits to the temporary structures.

CPS applicability in temporary structures monitoring

The realization of a complete CPS relies on several supporting technologies to integrate the virtual model with the physical construction (Akanmu et al. 2014). Although there have been no CPS applications for the temporary structures monitoring, some of the supporting technologies of CPS, such as Building Information Modeling (BIM) and Data Acquisition system have been utilized for enhanced monitoring of temporary structures. A brief review of these CPS supporting technologies' applications to temporary structure helps to identify their benefits and limitations, so as to provide a clear understanding of CPS applicability and potential benefits to temporary structure management.

Use of BIM for temporary structures management

For better virtualization of temporary structures, Chi et al. (2012) proposed to develop BIM objects of temporary structures, such as scaffolding system and formworks. These BIM objects will be embedded with design, construction and safety information as references to other parties. Similarly, a safety-rule based BIM for temporary structures (such as a scaffolding system), was developed, with special focus on automatically identifying and eliminating potential fall hazards during the design stage (Zhang et al. 2015). In addition to adding safety regulations to the BIM model of temporary structures, Kim et al. (2011) presented a safety identification system for temporary structures, which identifies and predicts potential safety hazard by simulating construction schedules and checking the location of temporary structures at each step. Besides, Li et al. (2008) proposed to integrate the design and construction of temporary structures through virtual prototyping. In view of the difficulties in identifying appropriate temporary structures to be shared among projects for cost saving, Kim et al. (2014) proposed the use of BIM technology for quick identification of sharing solutions of temporary structures among different projects. All of these efforts have benefited the visualization, design, and safety planning of temporary structures.

Use of DAQ for temporary structures management

A DAQ refers to computer based systems with digital input and output (UEI 2006). With developing technologies, DAQ has been recognized as important to prevent construction failures by providing information, and has been increasingly utilized for temporary structures management (Moon et al. 2012). These efforts include the use of Radio Frequency Identification (RFID), wireless sensor networks, and videos. As early as 2007, Yabuki and Oyama (2007) used RFID to record the usage history of temporary structures, so that project managers can understand how long the temporary structures have been used, in order to decide whether it is safe to keep using them. Ubiquitous sensor network technology can be used to determine the structural performance of temporary structures by analyzing deflection, load, strains, etc. (Moon et al. 2012). It provides a real-time approach to monitor formwork operations as a means of preventing structural failures. Most recently, Jung (2014) proposed the use of video method to detect potential defects of temporary structures. This system will continuously record the images of temporary structures, predict potential structural defects, and send warnings if there are potential hazards. With the development of DAQ, more structural information of temporary structures can be obtained for comprehensive structural analysis.

While the supporting technologies of CPS in temporary structures are still at the early stages of implementation, their benefits and limitations highlight the opportunities for further applications of CPS. Implementation of CPS in preventing failures and promoting safe construction techniques of temporary structures remains promising as discussed below.

POTENTIAL AREAS FOR CPS APPLICATIONS IN TEMPORARY STRUCTURES

For the purpose of identifying potential areas for CPS application, temporary structures which have historically been involved in a high record of failures were selected for discussion. These cover two general categories - temporary performance stages and temporary support systems.

Temporary performance stages

A temporary performance stage is a structural assembly that is used for an outdoor performance for less than 90 days of one year (Wainscott 2011). Collapses of temporary performance stages have occurred frequently in recent years. In 2008, two of the stages for the Rocklahoma music festival collapsed, resulting in ten injuries when severe winds struck northeast Oklahoma. In 2009, the main stage of Big Valley Jamboree in Toronto collapsed, killing one and injuring at least seventy people during another wind storm. Additional collapses occurred in 2011, including the well-publicized Indiana State Fair Grandstand, resulting in multiple fatalities and over fifty people injured in total. More recently, the Downsview Park in Toronto collapsed in 2012, killing one person and injuring three others, while another stage roof collapsed in North Carolina in 2013 during bad weather (Kleinosky 2012). These accidents are also related to the lack of authoritative standards for temporary structures and performance stages (McKinley 2011). This makes the need for a proactive monitoring system more urgent (Yuan et al. 2014).

Temporary support systems

Temporary support systems serve to help carry or support a structure or provide safety access for workers during the construction process. They are categorized into four types (discussed below): scaffolding systems, earthworks, formwork, and temporary bracing systems.

Scaffolding is used to provide temporary safe working platforms for the erection, maintenance, construction, repair, access or inspection of structures or other building systems (Grant and Pallett 2012). According to the U. S. Bureau of Labor Statistics, approximately eight workers working on scaffolding system are hurt each month at the United States construction jobsite (BLS 2013).

Sheeting and shoring (using systems such as steel soldier piles, sheet piles, and slurry walls) are used to prevent soil movement and cave-ins during earth excavations. Inappropriate design and installation of earthwork shoring and sheeting systems results in numerous accidents each year, making earthworks a substantial risk for workers.

Formwork systems are primarily used for standard poured-in-place concrete construction. Formwork construction is associated with a relatively high frequency of disabling injuries and illness (Hallowell and Gambatese 2009). This is now recognized as a serious problem (Shapira 1999).

Temporary bracing systems are used to keep a structure or building system stable before the permanent bracing is installed or the element becomes self-supporting. Insufficient bracing is cited as one of the four top causes of failures in steel structures under construction (Kaminetzky 1991). The structural load is usually analyzed by conceiving the whole structure as a completed entity, and there is frequently a lack of design or proper implementation of the temporary bracing systems. Often, the specific provisions and requirements of temporary bracing systems are left to the workers on the job site that may not have the qualifications or expertise for proper execution (Feld and Carper 1996).

Application scenario

Scaffolding system, listed below, has been selected for the analysis of CPS application in temporary structures monitoring for two reasons. First of all, scaffolding systems, ranking third among top 10 OSHA violations in the year of 2013, accounts for a large amount of fatalities and injuries in construction industry (U.S. Department of Labor 2014); second, the principles of structural monitoring of scaffolding system are similar to the ones of other types of temporary structures, which indicates that the TSM of scaffolding system can be easily adopted by other temporary structures.

Workers and equipment on scaffolds have the capability to impose movement or inclination that exceeds design limits, which in turn can result in collapse. Unfortunately, it is often left to workers to determine if the scaffolding is overloaded, shifting or otherwise not performing as intended (Feld and Carper 1997). In such cases, CPS can be used to monitor the movement and load conditions imposed by the placement of materials and the movement of workers on the scaffolds. For example, a sensor can be attached to the scaffolding to continuously detect its loading information, and send dynamic response data to a virtual model. Based on structural analysis and performance parameters, the virtual model can be updated with the live condition, predict the stability of the scaffolding and, when appropriate, issue an instruction to the actuator on the job site or to site personnel to take appropriate precautionary measures. For example, hydraulic cylinders can be place at the side of scaffold posts as actuators. Upon identification of early signal of inclination, these actuators act to hold the inclined posts according to system commands. In addition to the remote control of actuators, the project manager or structural designer can also send instructions from the virtual model to the physical component on the job site to guide workers' activities. An application scenario for structural monitoring of scaffolding using CPS is illustrated in Figure 1.

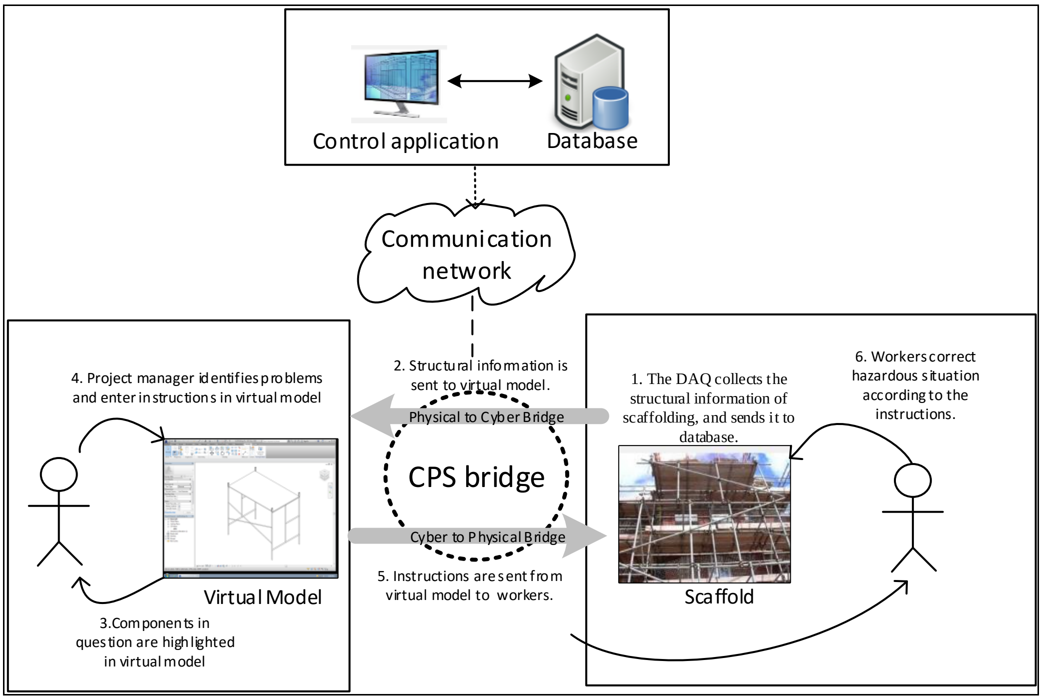

Figure 1: CPS application scenario of structural monitoring of scaffolding

As identified in Figure 1, a CPS can be developed for structural monitoring of scaffolding systems by enabling bi-directional communication between the Physical scaffold components and their virtual models. To be specific, first of all, the DAQ placed on scaffold components on the job site collect structural data (such as information of inclination, loading, deflection, etc.) and send all data to the database; Second, the structural information is continuously inquired by the virtual models for structural performance analysis; Third, the virtual models are updated based on the most recent structural analysis. Once there is potential hazard, the components in question will be marked in red color for attention; Fourth, once received the warning, project managers and competent person analyze the structure performance of scaffolding system in virtual model and send instructions through virtual models to the DAQ or other portable devices; Finally, workers act to correct the situation based on the instructions.

POTENTIAL BENEFITS AND BARRIERS

Based on the section of “key features of CPS” and “applicability of CPS in temporary structures” discussed above, several potential benefits and barriers to CPS implementation are identified as follows.

Potential benefits

CPS offers the potential for improved monitoring of temporary structures through real time coordination between virtual and physical systems. By systematically implementing CPS, a number of potential benefits can be achieved as follows:

- ***Real time inspection:*** in lieu of inspecting specific influential factors, CPS can monitor the performance of temporary structural components in real time, and provide warnings that can help to ensure structural stability.
- ***Tight coordination between physical component and virtual model:*** CPS enables bi-directional communication between physical components and their virtual representations. Through the “Physical-to-cyber Bridge”, the movement of physical

components will be detected by sensors and sent to the virtual model, where the difference between designed and actual structure will be highlighted on the model. Through the "Cyber-to-physical Bridge", once potential hazards are detected, safety alerts or instructions can be sent from the virtual model to the workers or a mechanism to automatically stabilize temporary structures can be actuated if appropriate.

- ***Remote and multi-party access for management:*** due to the bi-directional information loop between the physical and virtual components, the structural performance can be remotely monitored using virtual models. CPS enables multiple parties to obtain access to the structural monitoring system from different locations through the interface of virtual models. This function benefits project managers, structural designers, owners and other involved parties for routine monitoring, potential structural problem analysis, instruction to avoid potential dangers, and enhanced collaboration.
- ***Early warning with customized safety level:*** Implementation of a dynamic CPS environment has the potential to shorten the time interval between the on-set of an initial hazard and potential collapse. In addition to the quick identification of potential problems, the system can prevent hazardous situations by setting a safety factor for the performance of temporary structures. In this way, instead of having alarms when there are already structural failures, an early warning will be sent once there is a trend or high possibility of potential structural failures. The safety factor can be used as recommended or customized if the user wishes to have a higher level of safety.
- ***Knowledge base to predict potential hazards:*** during the structural monitoring of temporary structures, all the performance data of the temporary structures and instructions at different situations is recorded in database. The relationship between instructions and structural problems can be learned and identified, which enables CPS to automatically provide suggestions for instructions when having similar structural problems.

Potential barriers to CPS implementation

The preceding discussion has demonstrated that there are several temporary structures applications that can benefit from the implementation of CPS for monitoring and performance purposes. However, there are also barriers and technical issues to be addressed. Some of these include:

- ***Security:*** There is growing concern about cyber-attacks on CPS, as computing systems and sensor networks are unable to work effectively under malicious attacks. Furthermore, attacks on CPS used in commercial business or hospital environment might disclose personal information (Cardenas et al. 2008).
- ***Reliability:*** Random failures in CPS may occur due to system errors, inaccuracy of data, and data interference. Sensed data is susceptible to a reduction in accuracy due to interference from other signals such as Wi-Fi or other electronic devices (Akanmu 2012). However, modern construction job sites involve numerous kinds of electronic equipment which impacts the accuracy of sensed signals. Physical damage to a sensor due to construction operations or impact is also a possibility.
- ***Training of workers:*** CPS involves the management and installation of new technologies, including hardware such as sensors and actuators on job sites. These technologies need to be implemented, tested and inspected on a continuous basis. It requires that construction personnel are adequately trained in the use of these new technologies.

- ***Financial issues:*** although the price of sensors has dropped, accurate and quick detection requires a large number of sensors to work simultaneously. In addition, the use of actuators, the connection system between sensors, information platform and actuators, and the training of workers have cost implications that will need to be addressed.

SYSTEM REQUIREMENTS AND ARCHITECTURE

In order to use CPS for enhanced temporary structures monitoring, one should identify the system requirements, so that the expected benefits of CPS in temporary structure can be achieved. Based on the identified system requirements, a system architecture is presented as an example of how CPS works in temporary structures monitoring.

System requirements

A summary of system requirements is presented below under appropriated headings:

Visualization

The requirements of visualization include two aspects – visualization of temporary structures in question and the visualization of instructions. The virtual model of temporary structures is one of the basic parts of CPS, which provides user interfaces for remote inspection and control of the physical model. The virtual model should be consisted of digital components which unique ID, so that can be recognized and inspected independently by computing system. It is recommended that the virtual model provides basic properties and information of temporary components, which assists project managers in structural analysis and decision making in preventing potential collapse. Besides, the instructions entered in the virtual model will be sent to the DAQ or portable devices. To avoid misunderstanding, the instructions, along with the picture identifying the components in question should be presented clearly to workers.

Real-time and Remote Communication

To enable real time and remote interaction between the temporary structures and their virtual models, continuous wireless connection must be set up. Since the temporary structures work in a dynamic environment, the monitoring of the updated structural status of a temporary structure should be in real-time, so that potential structural defects can be quickly identified and an early warning issued before accidents occur. An example of such a network is Socket, which is an endpoint for communication between two machines. Database can be used both for data storage and real time data communication between virtual model and the physical components.

Adaptability between Virtual and Physical World

Adaptability is a big concern when identifying the hardware and software for CPS implementation. To enable customized function at the interface of the virtual model, the software used for virtual model development should provide an Application Programming Interface (API). Similarly, the software used for data acquisition or control devices, should also provide an API so that a control activity can be initialized on the control devices when needed. Besides, the data format should be well examined to make sure that the information exchange at the database platform between DAQ and the virtual model works well.

Data Precision and Resolution

The structural analysis of temporary structures has a high requirement for the data accuracy and resolution, because of the potential for failures due to the dynamic construction environment. The data accuracy should be as high as 95% for an accurate and confident level of structural analysis. Besides, the selection of the resolution of the DAQ is based on the level of details of temporary structures performance to be checked. It is recommended to use the one with appropriate level of precision due to concern of noise interference (Moon et al. 2012), so that more detailed structural performance of temporary structures can be captured.

System Security

Two concerns should be addressed for system security: continuous information exchange between temporary structures and virtual models, and the accuracy of system logic for correct system response. Real-time structural monitoring is based on a continuous information exchange loop. If there was an interruption or noise that disrupts the connection of the information exchange, the real-time monitoring of temporary structures would fail. Therefore, a back-up connection should be designed to keep the system working well even when the primary connection between temporary structures and virtual models is broken. The second concern is to make sure that the system will respond as designed under different circumstances. Take the hydraulic cylinder for example, as we discussed before, the hydraulic cylinder placed by the side of scaffolding posts can be used to hold the inclined post so as to prevent potential collapse. However, if the cylinder didn't work due to system error, the collapse would never be prevented. In general, the system logic should be well tested for security consideration.

System Architecture

The CPS for temporary structures monitoring consists of physical temporary structures and their virtual models, which are integrated through a CPS bridge. According to the system requirements identified in the previous section, the system architecture is demonstrated in Figure 2. The CPS bridge provides bi-directional communication between physical and cyber system through the use of communication networks and databases. To enable the information access to physical temporary structures by the cyber system, a DAQ is attached to the physical structures; for human-machine interaction and remote inspection of the physical structures, a BIM plug-in is developed at the end of virtual model; besides, the portable devices are used as communication tools between cyber system and safety professionals whose corrective action to the physical structures are made based on the instructions from cyber systems.

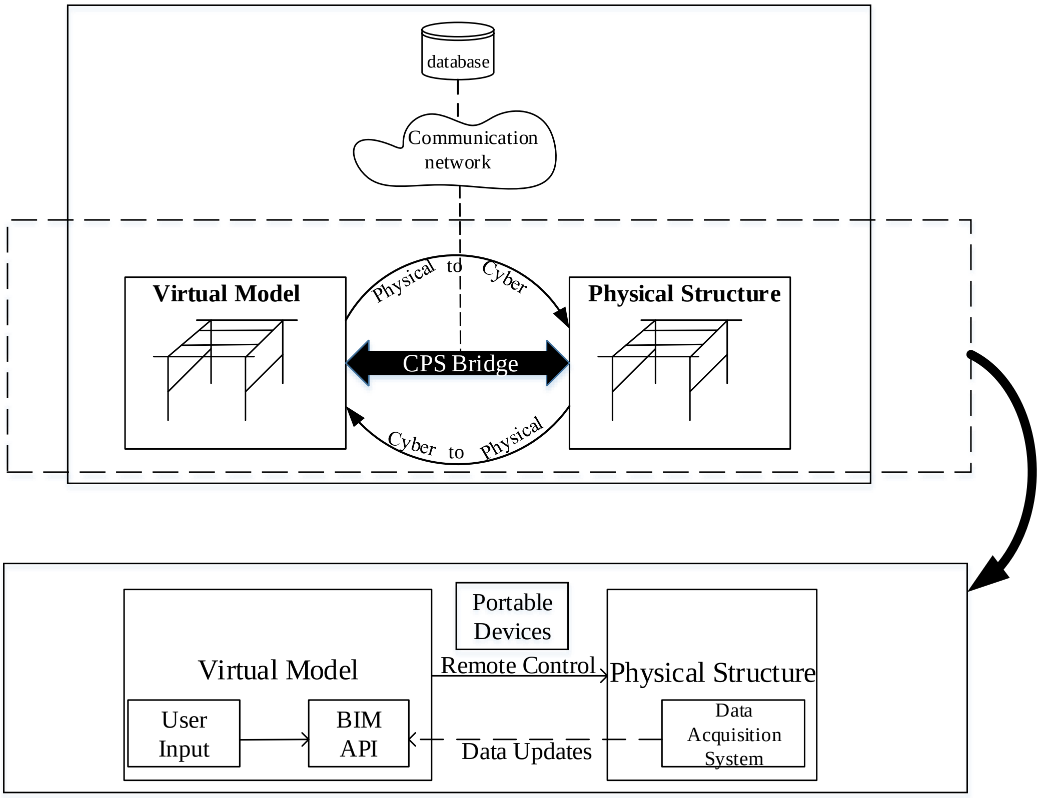

Figure 2: System architecture

While the use of CPS has been highlighted as a promising solution to temporary structures, a few limitations should be pointed out for further exploration. First of all, there is a lack of guidance to the selection of DAQ technology for different application scenarios. Based on the objective and characteristics of objects to be monitored, different DAQ approaches (such as image-based approach and embedded sensors) should be used for to support the development of CPS; Finally, the difference between the construction industry and other industry sectors requires careful design of control methods from the virtual model to the physical structures. Due to the dynamic working environment on the construction jobsite, an unexpected change or control of the performance of temporary structures may put the construction workers nearby in danger. This can be taken care of by taking into consideration the space and working relationship between the construction workers and the temporary structures.

CONCLUSION

Based on the preliminary literature review, a CPS was proposed as a potential solution for monitoring the stability of temporary structures. The current problems of temporary structures and key features of CPS have been summarized to establish the need for CPS in temporary structures monitoring. A typical type of temporary structures, scaffolding system, is analyzed for CPS applicability. However, due to the similar principles of monitoring most of the temporary structures, CPS application can be expanded to other types of temporary structures as well. Besides, the potential benefits and barriers to CPS implementation in temporary structures have also been identified. For better understanding, a system architecture with system requirements is proposed as an example of how CPS could be implemented for temporary structure monitoring.

A number of key conclusions can be drawn from this study. Generally, the temporary structures failure remains a big risk to the safety management of construction projects. The inadequate monitoring of temporary structures calls for a more proactive, intelligent monitoring system, such as CPS. CPS provides an effective way of integrating the real world with its virtual representation, and has been implemented in several industry sectors, such as the manufacturing industry, power grids, the transportation industry, and the healthcare industry. More recently, CPS has shown potential benefits to the built environment through its successful application in structural health monitoring and facility management. Therefore, CPS offers an opportunity to address the current problems and safety issues associated with temporary structures, including temporary performance stages and scaffolding. To be specific, a CPS for temporary structures monitoring enables remote control, "on physical component instructions", and real-time interaction between temporary structures and their virtual representations. Finally, a CPS for temporary structures monitoring can be developed based on the system requirements and system architecture presented in this paper.

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A CONCEPTUAL FRAMEWORK OF IMMERSIVE SHARED ENVIRONMENTS EMPHASIZING SOCIAL INTERACTION

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Abstract
The effectiveness of visual displays has often been linked to the sense of presence embodied by immersive visualization. However, efforts analyzing how presence is associated with multi-users' quality of communication, including visualization capabilities to assist in architecture, engineering and construction (AEC), are still unfolding. This research is an exploratory study on social interaction, which aims to improve the presentation and communication of complex data through immersive simulation techniques. This paper reviews key concepts such as presence and immersion to identify factors that influence communication in the representative literature. It then introduces the Hub for Immersive Visualization and eResearch (HIVE) with a focus on the technological components. Finally it presents a conceptual framework of immersive shared environment, which enables multi-users to understand how to implement social interaction in a system efficiently or to determine whether a visualization system could support communication effectively. Future studies to validate the proposed framework are discussed, particularly in the context of cognitive factors in a shared environment.

Keywords: *Social Interaction, Presence, Immersion, Visualization System, Shared Environment, Communication*

INTRODUCTION
Considerable research has been conducted on immersive environments with a focus on issues of technology itself, and many researchers have assumed the benefits of immersive visualization for task performance (Arns et al., 1999; Gruchalla, 2004). The effectiveness of visual displays has often been linked to the sense of presence embodied by immersive visualization, and presence is often thought to be concomitant with immersion (Slater and Wilbur, 1997; Witmer and Singer, 1998). For example, presence, the subjective experience of being in one place, can be effective in itself for certain applications such as games and simulation. People use immersive visual systems to represent their ideas and receive feedback in collaborations. Virtual Environments (VEs) are an effective interface that delivers design information in 2D to 3D representation. Research on presence has primarily focused on personal presence and made noted efforts in identifying its contributing factors and measurement (Witmer and Singer, 1998; Schubert et al., 1999; Schubert et al., 2001). However, research on the association of presence with multi-users' quality of communication, including visualization capability to assist in the domains of architecture, engineering and construction (AEC) domains, is still unfolding.

This research is an exploratory study on social interaction, which aims to improve the presentation and communication of complex data through immersive simulation techniques. The Curtin Hub for Immersive Visualization and eResearch (HIVE) consists of four large-scale visualization systems that enable high immersive 2D and 3D visualization of different types of data, in varying volumes, scales and formats. It can create venues for social interaction through four displays to support communication and presentation in meetings, lectures or collaborative work among multi-users. Users' conversations are expected to be influenced by different levels of awareness in visual systems, which could affect their reflective thinking in performing tasks. For example, a person may be completely immersed in a dome type of screen, unaware of others who are outside the dome's boundary, whereas those using a cylinder type of screen may be aware of others because they are able to stay inside the cylinder screen's boundary. It can be argued that a low level of awareness of their surroundings hinders a person's social interaction in communication, whereas a high level of social awareness facilitates performance in collaboration. Nevertheless, having some sense of awareness in an environment is a necessary condition for communication in a shared environment.

This research explores how differences in social awareness under different visual interface conditions affect users' communication, and how these communicative differences eventually influence performance in training/education, decision-making and knowledge sharing. It develops and presents a conceptual framework of immersive shared environments in the context of social interaction, emphasizing multi-users' communication, with the aim of facilitating the strategic utilization and adoption of immersive environments for collaboration. The framework provides an alternative understanding of social awareness appropriate for creative performance in collaborations and a basis for evaluating future research on immersive shared environments. The potential for future empirical research to validate the proposed framework is discussed, particularly in the context of cognitive factors in a shared environment.

RESEARCH METHODOLOGY

This paper reviews significant works on cognitive issues in immersive environments, including earlier theoretical studies. Articles that concentrate solely on technical aspects of immersive environments are not included here. The paper first reviews critical concepts relating to the theory and implementation of immersive shared environments, such as presence, immersion, and integrated models. Next, it introduces the HIVE with a focus on the technological components. As visualization systems in HIVE will be adopted for case studies, essential functions are described and characterized in terms of their effectiveness in collaboration. Finally, a conceptual framework of immersive shared environments is constructed with a focus on social interaction and the practicability of each indicator for supporting communication in immersive shared environments.

IMMERSION, PRESENCE, AWARENESS AND CONNECTEDNESS

This section critically reviews a number of representative works on which much of the research on cognitive issues in immersive environments, such as immersion and presence, has been based.

Slater and Wilbur (Slater and Wilbur, 1997) described the concept of immersion quantifiably in terms of a visual system's capabilities of delivering an inclusive, extensive, surrounding and vivid illusion of reality. Inclusive indicates the extent to which the real world is excluded, while extensive indicates the number of sensory modalities accommodated by the system. Surrounding indicates the degree to which the display is panoramic, and vivid is concerned with the resolution and quality of the displays. Slater and Wilbur (1997) defined presence as a potential psychological and behavioral response to immersion in a mediated environment, where a user's compelling sense of being in a mediated space is the subjective response and a user's behavior similar to their behavior in reality is the objective response. Many VEs provide avatars to create a strong sense of personal presence since the distinction between self and non-self occurs at the boundary of the body (Heeter, 1992; Loimis, 1992).

Different types of presence have been proposed, emphasizing its utility in training/education, knowledge transfer and communication. Short et al. (Short et al., 1976) defined social presence as the "degree of salience of the other person in a mediated communication and the consequent salience of the interpersonal relationships", where "immediacy", measured by psychological distance such as nodding and smiling, and "intimacy", expressed by verbal and non-verbal behavior such as eye contact, are clearly related (Rettie, 2003). Novak (Nowak, 2001) distinguished social presence from copresence, arguing that the former relates to the medium and the latter refers to a psychological connection. He argued that copresence with another mind can be achieved with conscious awareness, assuming the interaction is mediated. Copresence was termed by Goffman (Goffman, 1963) as a sense of connection to and with another person, where users can perceive others and feel that others can perceive them. Attention or responsiveness to others is important in copresence (Ciolek, 1982).

Environmental presence refers to the reaction of the environment to a user, which can provide evidence of the user's existence (Heeter, 1992). The user's ability to modify the environment is an important factor in achieving environmental presence (Sheridan, 1992). In a similar context to environmental presence, Schubert et al. (Schubert et al., 1999) proposed embodied presence, which emerges from interactions with an environment as the possible bodily actions in the VE. Embodied presence emphasizes the environment's role in the development of cognitive processes and embodied action. Important tasks supported in immersive systems may be 2D/3D configurations to represent objects; thus object presence, the subjective experience of being co-located with a set of objects in a user's environment, would be a critical concept for the performance (Stevens and Jerrams-Smith, 2001). Object presence is often thought to be linked to scene depth, requiring physiological depth cues such as stereopsis and motion parallax, and supported by a high resolution display, a wide field of view and the addition of audio and haptic modalities (Sheridan, 1992; Rokita, 1996)

"Connectedness oriented communication", defined by Kuwabara et al. (Kuwabara, 2002), allows people to be aware of each other and contributes to the maintenance of social relationships. Dourish and Bly (Dourish and Bly, 1992) defined awareness as "an understanding of the activities of others, which provides a context for your own activity", which means both a perception of the users and an aspect of a system enabling that perception. Rettie (Rettie, 2003) found that the need for connectivity was the most important factor in making a choice between communication channels and suggested logical relationships between social presence, connectedness, and awareness. Awareness can occur without social presence or connectedness; connectedness is related to awareness and can occur with little or no social presence. They include an "awareness of object" in addition to an "awareness of another person" to describe the experience of connectedness to an object rather than to a person. Connectedness is similar to the concept of copresence because it is a feeling of psychological involvement as well as an emotional experience.

The focus of this literature review was to identify key concepts associated with social interactions – immersion, presence, awareness, and connectedness – and to clarify them in the context of the immersive shared environments, emphasizing cognitive issues. Factors that influence communication in collaboration were extracted based on a comprehensive understanding of those concepts.

CHARACTERISTICS OF IMMERSIVE VISUALIZATION SYSTEMS IN HIVE

Each of the four large-scale visualization systems in HIVE has unique characteristics to suit particular types of content with varied media representations. First, the Tiled Display, comprising 12 full-HD LCD panels (24 million pixels) in 10 square meters, supports the presentation of ultra-high-resolution images, including multi-megapixel mosaics, or even giga-pixel-sized panoramas. Second, the Cylinder, three-meters high and eight meters in diameter, is designed for the presentation of immersive stereoscopic panoramas, where a tracking system can be fitted for displaying in stereoscopic 3D. Three high-end projectors are warped around the 180 cylindrical surfaces to provide a continuous display of five megapixels. Third, the Wedge consists of two rear-projected 3.8-meter diagonal displays, mounted in either a 90-wedge configuration or a double-wide flat screen. It presents stereoscopic 3D content such as scientific 3D volume visualization and 3D video content. Fourth, the Dome provides an immersive experience via a four-meter diameter domed screen that entirely fills the observer's peripheral vision. It can be used to explore 360 ultra-realistic panoramas and omnidirectional video.

As input devices, a spacemouse with 6 degrees of freedom, wireless XBox controllers, and Kinect v1 for makerless motion capture can work in four visualization systems. Capture devices include Red Scarlet with 14 megapixel stills, 4K video and Canon EF lensmount. Canon 5D with 20 megapixel stills and 1080p video and Sony TD10 with 3D video camera. For augmented visualization, a Headmounted 3D display can be installed in the four systems, but OptiTrack InfraRed cameras, capture motions using retro-reflective dots, can be operated in the Cylinder only. Over 25 software packages are installed in the system for 3D modelling from images, CAD, rendering, panorama stitching, scriptable virtual interaction environment, volume visualization from CAT/MRI scans, point cloud visualization and manipulation, and visualization of seismic data so forth. With affordances and functions, HIVE can provide powerful immersive environments for training/education, presentation, and collaboration in all disciplines, creating many opportunities for sharing information efficiently and facilitating new modes of creative expression.

The Tiled Display | The Cylinder | The Wedge | The Dome

Figure 1. Four visualization system (Source: HIVE in Curtin University, Australia).

According to Slater and Wilbur's arguments (Slater and Wilbur, 1997) that the degree of immersion has an influence on presence, stereopsis and a wider field of view contributing vividness and spatialized sound contributing to the extensiveness are positively correlated with reported presence (Hendrix and Barfield, 1996a; Hendrix and Barfield, 1996b). The four visualization systems create immersive environments affording different degrees of inclusive, extensive, surrounding and vivid illusion, which might affect social interaction among users. For example, surrounding illusion can be delivered by the large screen of the Tiled Display and the wider field of view of the other three systems, while inclusive illusion can be delivered by the entire peripheral vision of the Dome where the external reality is not perceived by the users. The dynamic 3D objects of the Cylinder and The Wedge and the high-resolution images of the Tiled Display can provide vivid illusion in the immersive environments. Extensive illusion can be manipulated through additional interfaces installed in each system according to the task context employed and users' preference for various sensory modalities. These features of HIVE can be utilized effectively to validate the proposed framework in case studies, addressing cognitive issues and challenges for the implementation of the immersive shared environments.

A CONCEPTUAL FRAMEWORK OF IMMERSIVE SHARED ENVIRONMENTS

Based on the critical review of concepts and models, a conceptual framework was developed to elucidate the understanding of social interaction in immersive systems. The proposed framework conceptualizes the effects of social interaction on communication and task performance in a shared environment. The framework might be useful for developing immersive shared environments and interpreting empirical studies on social interaction in visualization systems. It could provide a guideline for the implementation of the systems and metrics for the analysis of the empirical data. Social presence, copresence, and object presence, which influence communication and performance, are mainly considered in the proposed framework. The more subtle experiences, such as gaze awareness of who is looking at us, when people join a meeting, where group attention is focused, and the ability to share in the manipulation of objects, are essential for supporting communication in multi-user systems (Slater and Wilbur, 1997). The three levels of the framework represent the interactions of users, systems and collaborative tasks.

Table 1. Conceptual framework of immersive shared environments

User	Presence indicator	
Spatial presence	Transportation	Feeling of being there in the generated world
		Feeling of being here in the real world
	External awareness	Awareness of surrounding objects
		Awareness of other people in the surroundings
		Awareness of surrounding sounds
Social awareness	Copresence	Feeling of connection to and with another person
		Perception of others and others' perception of them (mutual awareness)
		Feeling of understanding (goals, needs, etc.)
	Social presence	Awareness of users' activities
		Awareness of small gestures such as nodding and smiling (Immediacy)
		Awareness of non-verbal behavior such as eye contact (Intimacy)
Involvement	Psychological involvement	Mutual understanding of activities
		Engaged senses in performing a task
	Behavioral engagement	Behavioral independence
		Mutual assistance
	Experience	Adjustment to the real-/generated world experience
		Involvement in a task (losing track of time)
System	**Technology Indicator**	
Immersion	System awareness	Interface awareness (display, control devices, etc.)
		Lag or delay in the generated world
	Capability	Delivering inclusive, extensive, surrounding and vivid illusion of reality
		Auditory aspects of the generated world
		Information/experience consistent with the real world
Interface	Control factor	Control devices
		Environment modifiability
		Control mechanism (comfort level)
	Sensory factor	Multimodality
		Naturalness of manipulation
		Interactivity (action, response etc.)
Object Presence	Realness	Visual realism of objects (depth, volume etc.)
		Feeling of objects moving through the generated world
		Feeling like grasping objects
	Manipulation	Looking around the generated world
		Manipulating objects in the generated world
Task	**Requirement Indicator**	
Purpose	Application	Applied domains: architecture, engineering and construction
		Supporting works: training/education, planning, brainstorming, decision making, etc.
Activity	Communication	Communication channels (text, visual and acoustic media)
		Naturalness of communication
	Representation	Geometric vs. non-geometric
		Images vs. data (information and knowledge presentation)
	Work space	Individual vs. collaborative work
		Private vs. shared space

As shown in Table 1, the framework comprise eight categories at three levels of immersive shared environment: spatial presence, social awareness, and involvement at the User level, immersion, interface and object presence at the System level, and purposes and activities at the Task level.

The User level represents users' perception and experience when they work in the generated world. "Spatial presence" represents the presence of spatial elements in places, which largely describes the sense of being presented and an awareness of the surroundings. "Social awareness" represents users' social interaction and relationship, which could be measured by copresence, associated with the other persons' involvement in the interaction, and social presence, associated with the perception of the medium's ability to provide social awareness. The "Involvement" category, concerned with the allocation of attentional resources, comprises psychological involvement, including mutual understanding and engaged senses, behavioral engagement emphasizing the behavior interaction, and users' experience of the medium. It is important to develop a measure that truly evaluates the extent to which people feel a sense of being there and the connectedness to the other mind in the generated world.

The System level represents the physical characteristics and technologies of the system for an immersive shared environment, emphasizing the sense of the objects, which leads to the concept of immersion. "Immersion" represents an objective description of display technology, such as the stimuli from reality, the range of sensory modalities, the field of view, and the display resolution. The "Interface" category includes control and sensory factors, which are associated with the technical side of the immersive system and used to assess the properties of the interaction between user and the system. Linked to a display supporting users' real-world skills for a task, "object presence" represents the sense of a collection of objects being present or moving in the generated world, and the sense of ease with which the object can be manipulated. Realness is a subjective way of measuring the reality of the generated world. Although it is not part of the actual experience of presence, realistic reactions are one of the important consequences of presence.

The Task level represents the application areas and requirements of the tasks that users must perform in a shared environment. The nature of the task may influence the amount of attentional resources for the task, which may affect the quality of communication and representation as the users perform the task in the immersive shared environment. Stevens et al. (Stevens et al., 2002) argued that new measurement methods are needed to assess presence by more closely considering task requirements and how naturally a display supports a user for specific purposes. For example, some tasks do not require the user to be surrounded or isolated and presence is more dependent on coherence rather than immersion (Slater & Wilbur, 1997). It is expected that immersive shared environments help to transfer users' learning from the virtual tasks back into the real world. Work tasks include activities such as solving a problem, developing a plan, disseminating information and knowledge, negotiating, and reaching consensus.

CONCLUSION AND DISCUSSION

This is a preliminary study to determine if social interaction affects the quality of communication and task performance in collaboration. Based on a critical review of the literature, a comprehensive framework of immersive shared environments for AEC was developed, focusing on communication in visualization systems. The notion of presence does not simply imply realism but is related to the environment in which a participant is acting (Slater and Wilbur, 1997). From this perspective, the research question was drawn: what display characteristics are relevant to the AEC domains, maximizing presence? Sometime, a non-realistic display enhances presence, or characteristics enhancing presence are not the same as those supporting a particular type of task performance. The type of task will affect a user's sense of presence and task performance; thus presence can be determined by asking for what purpose a user should present and then finding minimum factors required for creating presence for that task (Zeltzer, 1992; Bystrom et al., 1994). The proposed framework consequently comprises three levels - user, system, and task - associated with social interaction.

So far, only limited efforts have been made to systematically position concepts in immersive environments in a framework for theory and implementation. This paper proposed a framework that considers issues relating to the effectiveness of immersive environments in supporting communication. Its metrics can help to define the parameters of immersive systems and tailor questionnaires to the specific media. The framework can be used to determine important factors that influence social interaction, providing a theoretical basis for research on immersive visualization systems and their development for collaboration in AEC domains. It may therefore help designers select appropriate display features when they construct immersive systems for communication and presentation. The framework categorizes existing research streams, guides research efforts, and reviews the critical issues.

Future research could focus on the effect of social interaction on each visual interface and how this could affect the collaborative design process from a cognitive perspective. In addition, the effects of shared environments on people's understanding in design presentation should be investigated in different visual interface conditions. We plan to conduct a series of studies on social interaction in order to examine how four different displays influences users' subjective sense of connectedness and design communication, thereby affecting task performance within design.

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DESIGNING IN CAVES: USING IMMERSIVE VISUALISATIONS IN DESIGN PRACTICE

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Abstract
This paper describes a study of the use of immersive Virtual reality technologies in the design of a new hospital. It uses Schön's concept of reflective practice and video-based methods to analyse the ways design teams approach and employ a full scale 3D immersive environment – a CAVE – in collaborative design work. The analysis describes four themes relating to reflective practice occurring in the setting: orienting to the CAVE technology itself, orienting to the representation of the specific design within the CAVE, activities accounting for, or exploring alternatives within the design for the use and users of the space, and more strategic interactions around how to best represent the design and model to the client within the CAVE setting. The analysis also reveals some unique aspects of design work in this environment. Perhaps most significantly, rather than enhancing or adding to an existing understanding of design through paper based or non-immersive digital representations, it is often acting to challenge or surprise the participants as they experience the immersive, full scale version of their own design.

Keywords: *CAVE, design teamwork, immersive virtual reality environments, reflective practice*

INTRODUCTION

The combination of increasing awareness and use of Building Information Modelling (BIM) as a set of collaborative processes and developments in the availability and range of visualisation technologies accessible to practitioners is enabling new ways of performing design and construction activities. The availability of building information models has provoked new interest in the use of virtual and immersive technologies.

There is an extensive and well-established literature addressing the potential and use of virtual reality (VR) and immersive virtual reality (IVR) for design and construction. The themes addressed range broadly across technology development and piloting, experiments and case studies of use (Kahkonen, 2003). For example, Goulding and Rahimian (2011) raise attention to new social interactions and decision-making criteria enabled by such technology and indicates the potential of using VR for simulating scenarios of construction activities. This might lead to a safer environment for training AEC (Architecture, Engineering and Construction) professionals to deal with the challenges occurring in real-life situations of practice (Goulding et al., 2014) or to fostering practitioners' creativity and ability to engage with non-routine AEC activities (Rahimian et al., 2014). Another theme is integrating VR in design processes through developing and testing technology to enable more intuitive interaction with the model in the conceptual phase (Ye et al., 2006), or to better support the users' involvement in the design process (Petric et al. 2002). Feasability studies have shown how VR can support design in conceptual phase, with a focus on the impact on the cognitive and collaborative processes involved (Rahimian &Ibrahim 2011).

Whyte et al (2000) investigated the practical use of VR technology in the industry.

This paper contributes to this literature through a concern with issues of understanding and reflecting on the effects of immersive technologies on construction design activities as used in concrete 'real-life' settings and as perceived by the practitioners involved. The setting being studied is the design of a new hospital in the UK with all patient accommodation as single rooms. There are particular client requirements around the size of the rooms, and the visibility of patients from nursing stations. Models of the single rooms were imported from CAD (Computer Aided Design) models into a CAVE –a full scale 3D immersive environment set up in a UK University lab. Over six sessions, the design teams used the CAVE to review the design against the client requirements. Adopting Schön's (e.g. 1983) perspective of reflective practice, and employing video-based methods, this paper discusses insights around the design processes occurring in the CAVE, the activity around presenting the models to the NHS (National Health Service) client and its use in demonstrating particular design requirements, and more generally around how the project teams are exploring the CAVE as a design work setting.

DESIGN AS REFLECTIVE PRACTICE

Reflective practice – An overview and key concepts

The conceptual positioning of this study is based around Schön's (1983) theory of design as 'reflective practice', which considers design as a process of both reflecting and acting, or 'thinking' and 'doing', that are inseparable and bound up in specific situations of practice. Schön positions design as a situated activity, across different individuals and materials incorporating design representations and technology. Reflective practice stresses the context dependent character of the process, accomplished through locally constructing and collaboratively sharing meanings to iteratively shape the design in responsive interaction with particular design situations. It is an open-ended process of making sense in situ, an interactive mechanism of defining and addressing, creating as well as discovering the situation. Design as 'reflective practice' is not a uniform process, but dependent on how it becomes configured in the unique, complex and messy situations of practice through both the individuals' specific ways of making sense of and approaching the situation, and through action.

It involves participants mobilising existing repertoires of knowledge, including prior understandings, and existing experiences and practices, to collectively make sense of and address particular situations. Importantly, there is an iterative relationship between what is brought in the situation to enact design work - the participants' perceptions, sense making, appreciative systems based on previous experiences and knowledge – and its outcomes which continually inform shaping of those repertoires. The media and materials in and through which the process is performed are also essential aspects of accomplishing practice. These materials cannot be disentangled or separated in their contribution to configuring and developing the process (e.g. Schön, 1983:271).

Overall, Schön argues that design as reflective practice is realised individually and collectively through reflecting and acting, drawing on appreciative systems and repertoires, and through engagement with the materials and media in the situation.

Reflection-in and reflection-on action

The essence of 'reflective practice' resides in that the 'thinking' and 'doing' are inseparable and linked through reflection which mediates enacting knowledge in response to specific situations to address the unfamiliar, unexpected, surprise instances non-approachable in routine ways.

It distinguishes two states as reflection –in and –on action. The first refers to thinking while performing the actions, and the second is a form of thinking back to action previously accomplished outside of the situation. This is a process of connecting with the understandings developed during action (Schön, 1992:126), enabling ‘constructing an understanding’ and shaping of the situation. Reflection-in-action is about understanding the situation while and through attempting to shape it. It involves thinking about the actions while performing the process. In Schön’s words, the practitioner(s) is (are) reflecting-in-action “on the phenomena before him and on the prior understandings which have been implicit in his behaviour” and, in group contexts, “on the collective accomplishment of their practice and on the individual contribution to it” (Schön, 1983:68). It is configured “not necessarily through words, but through developing a ‘feel for’ the situation” in an “experiment of generating new understanding of the phenomenon and of changing the situation” (id.). The idea of reflection-in-action suggests the interconnectedness of perceptual mechanisms oriented to both understand and change the situation through action (Schön, 1983:134), i.e. both making sense of and shaping the design for accomplishing the process through social and material interaction.

Design as reflective conversation with the materials of a design situation

A key idea regarding design as ‘reflective practice’ is of understanding the process of addressing a design situation as transactional, in the sense of ‘conversation’ with others, and with the materials – the media and representations involved (e.g. Schön, 1984; 1991; 1992). Design is inquiry bound up in particular context through locally constructing meanings of the ‘materials and messages’ (other’s understandings) in an ongoing process of shaping and being shaped by ‘talking-back’ to the situation (Schön, 1992: 126-127). This transactional, or interactional perspective on the process emphasises its situated character and the responsive, ‘conversational’ nature of design interactions with materials, meanings, and people, and the relationships between. ‘Design as reflective conversation with the materials of a design situation’ is inquiry mediated by conscious reflection on the situation and on the ways of thinking and doing employed to address it (Schön, 1992: 126). It stresses the role of the materials of a design situation in shaping the ongoing process of responding to the emergent changing states of the situation drawn on previous interventions: “Any faithful description of designing must take account of the fact that designers work in a medium [for example drawing on paper] and literally see the evolving products of their work.” (Schön & Wiggins, 1992: 154). As the transforming situation ‘talks back’, it brings about discovery of new meanings which will inform the further process driven by “workable understanding” (Schön, 1992:126). This is mediated through the way in which the appreciations drawn on repertoires of previous experiences are not rigid, but are also shaped during the process of attending to and accomplishing particular design events (Schön, 1983:151-152). The process of reflective conversation is stimulating further exploration. It connects with the idea of moving from exploration and initial understanding to experiencing in action, which drives continuous discovery.

An important feature in the process is responding to ‘surprise’ - unexpected, contradictory, unfamiliar states - mediated through ‘seeing’ the situation in new ways, in association with familiar elements of previous experiences, which guides the process of shaping the situation by employing action (e.g. Schön, 1983).

Other constituents interplaying with the media and the repertoires are social and material interactions. This point is described by Schön by referring to the process of engaging with the situation through ‘on-the-spot’ experimentation as undertaken in the ‘language of designing’ (1983: 80) i.e. the both verbal and non-verbal actions of orienting to the situation and to other participant’s actions. Importantly, the media, language and the repertoires are inseparable in their contribution in addressing the situation: “together they make up the ‘stuff’ of inquiry, in terms of which the practitioners move, experiment, and explore” (Schön, 1983:271). These means of engaging with the situation - verbal and non-verbal - are essential in understanding and transforming the design: “a designer’s knowing in action involves sensory, bodily knowing” (Schön, 1991: 7). This draws attention to the physicality involved in the designers’ processes of making sense of and engaging with the situation. In relation to this point, Schön draws particular attention to the role of the media in the manipulation of ‘virtual worlds’ as a means of imagining, understanding and testing the design before it is actually built, and stresses the importance of how the media, language and repertoires are being manipulated for configuring a feel for the situation (Schön, 1983:157-160).

The dynamics of reflection-in-action

Schön’s underlying concepts of reflecting and acting, in which the movement between the two constitutes the dynamics of the process, is described in several different ways, which can all be seen as an equivalent rehearsal of the cycle thinking-doing.

As such, the process is described as a flow of ‘seeing-moving-seeing’ (e.g. Schön, 1991:22; 1992), or as spiralling through stages of ‘appreciation, action and reappreciation’ (id., 1983:132), or as ‘active sensory appreciation’ (id.1991).The movement from reflecting to acting is explained as the iteration of stages of initial appreciation to formulation and realisation of intention of intervening on the situation, followed by appreciation of the consequences of previous intervention. The iteration reveals either confirmation of realisation of intention, or discovery of unintended consequences, which guides the further process by shaping the appreciations which will consequently drive following action.

Although Schön refers to the same consistent central ideas around the inseparability between reflecting and doing using different terms, often a distinction between stages appears to be implied and might be considered in tension with the core argument of reflective practice where thinking is inseparable from action. We address this point through discussing critiques of Schön’s theory and by drawing awareness on this conceptual duality in terms of mobilising Schön’s ideas to examine the empirical material.

Expressed by Schön in various shapes, the overall idea indicates understanding of design as ongoing process configured in iterative cycles of repeated experiments, shaped appreciative systems and understanding, or in other words through developing a ‘feel for’ the situation, and which, through generating cumulative discoveries, consequently inform, guide, stimulate further designing. This highlights Schön’s main idea on the dynamics of the practice which is the movement between thinking and doing, mediated through reflecting-in and -on action, which enables responding to surprise, in a process of developing a ‘feel for’ the situation through processes of appreciation of the situation and transforming the situation in series of on-the-spot experiments.

Critiques of Schön’s approach of reflective practice

As noted above, there is a possible tension between Schön’s underlying idea on the inseparability between reflecting and acting, thinking and doing, and the allusion to a distinction of spiralling steps (for example seeing-moving-seeing; appreciation-action-reappreciation). The literature reflects this tension in terms of the duality by which Schön’s work is both considering the process as a flow, as an artistry, configured through developing a feel for the totality of things of the situation, and in the same time, describing a structure in this process. This is related to Schön’s positioning against technical rationality and instrumental accounts of practice. For example, as Roozenburg and Dorst (1998) note, “Schön turns away from Technical Rationality , but he addresses design practice without crossing into irrationality: there is a structure in design activities which can be captured from the study of what (…) practitioners do. (…) Schön does not come very far in explicating the rigour in its own terms that he ascribes to the process.” (Roozenburg & Dorst, 1998: 40).

The study recognises this tension in Schön’s work with regard to understanding the process as linear versus circular, and acknowledges that this may be an attempt to demonstrate the depths of the process in a clearer way than can actually be observed in design performed in real-life practice. This awareness raises empirical questions around how traceable the stages of reflection-in-action are.

Other studies approaching design as reflective practice

The approach of the study builds on Schön's position as well as on more recent literature which, either by connecting broadly or by building directly on Schön's view on the process, restates the relevance of reflection in design or demonstrates the potential of mobilising reflective practice as means for understanding and analysing design work.

There is a wide range of seminal design studies connecting with Schön's ideas of reflective practice and adhering to Schön's (1983) argument around an "epistemology of practice implicit in the artistic, intuitive processes which [design and other] practitioners do bring to situations of uncertainty, instability, uniqueness and value conflict" (e.g. Cross, 2001a; 2007). This refers to reinforcing the shift from considering design as application of science to regarding it as a more complex process which is possible to be understood and explained by turning attention on the actual performance whereby the 'designerly ways of knowing, thinking and acting' are displayed to address the messy situations of practice (Cross 2001a).

The more specific ways in which these studies draw on Schön's position on design reflect their particular perspectives on the design process –for example as co-evolution of problem and solution spaces (Dorst & Cross 2001), or as solution focused process (Lawson 2006)-, and support addressing their concerns with distinct aspects around the design process. This consists in engaging with ideas of reflective practice from an interest with understanding issues of design cognition (e.g. DTRS 6, 2003), or from a focus on the social aspects involved in team designing (Cross & Clayburn Cross, 1995), from a concern with the use of computers in design (e.g. Lawson, 2005), to proposing theoretical models of design (Dorst & Cross, 2001; Lawson, 2006). Within the range of studies focused on design cognition, some examine the development of design expertise (e.g. Lawson 2005; Cross 2004), or take an interest in investigating design strategies and issues of problem formulation, and generation of solutions (e.g. Cross 2001b), or draw attention on the creativity aspect (Dorst & Cross 2001).

Among these studies broadly connected with Schön's ideas, the work of Cross (2001 b)- drawn on surveying a larger set of empirical studies on design cognition- indicates that the actual performance of design is influenced by the designers' perception, construction of tasks, and by the designers' goals. Drawing on Schön's idea of framing, Cross (2001b) also points that the designers' framings -i.e. their ways of seeing particular design situations - interrelate with the designers' decisions and consequent actions.

The work of Dorst and Cross (2001) proposes a view of design as process of continuous reflection on the evolving states of problem and solution spaces, an account encapsulated in the idea of a co-evolution model of design. Making a conceptual link to Schön's idea of (problem) framing and the notion of surprise, Dorst and Cross (2001) provide an account of design not as identification of problems and then searching for satisfactory solutions, but as a more complex process of iterating between developing and refining the understanding of both problems and solutions through engaging with a task or situation. Drawing particular attention to the creative aspects of designing their empirical analysis argues that creativity is related to a situated way of defining and framing the problem, and brings about the importance of the element of 'surprise' as essential for triggering reflection-in-action. Expanding on Schön's notion of surprise as interruption of routine, Dorst and Cross (2001) suggest that a 'creative event' in design is about realising a link between the problem and solution spaces, where this link is triggered by designers' identification of surprise. Therefore surprise shapes and changes the view of the problem, enabling the seeing of things in new ways and stimulating the process.

Another way in which this broader design area of design studies connects more directly with Schön's ideas is through Lawson's work (e.g. Lawson, 2004; 2005; 2006). Lawson's argument on the role of perception and memory of past experiences for accomplishing a new design (e.g. 2004, 2006) is parallel to Schön's idea on how the particular ways of addressing a design situation depend on the appreciative systems and the 'repertoires' of experiences and knowledge the particular participants involved draw on. Building on another core idea of Schön's position on design as practice, specifically the understanding of design as reflective conversation with the situation, Lawson (2005; 2006) stresses the role and the conversational or responsive nature of interactions with materials -representations and technology-, and other design participants. This presents an account of design as a process of thinking and communicating through developing representations of the design -for example by drawing.

Overall, adopting various perspectives on the process and focusing on a range of aspects around the performance of design work, these studies connect with Schön's view of design as reflective practice by considering design less as a scientific type of process, but as practical accomplishment, and realised through ongoing iteration of thinking and acting mediated through reflection. At the same time, this review finds a range of differences between the approaches adopted in these design cognition studies and the way in which this thesis takes forward Schön's conceptual position to examine design work. These differences result from their particular emphasis and focus on the cognitive aspects, arguably in detriment of showing the same attention to the 'doing' accompanying the 'thinking', and also from their tendency to aim for a generalizable understanding of the design process, potentially obscuring the situated character of design in practice.

Other studies engage more specifically with the ideas of reflective practice and mobilise related concepts in analysing empirical design situations. Some draw on Schön's theory in work examining and evaluating existing approaches to studying design (e.g. Dorst & Dijkhuis, 1995; Dorst, 1997; Stumpf, 2001). Other studies mobilise more explicitly ideas and concepts of Schön to investigate aspects of the design process in empirical situations (e.g. Valkenburg & Dorst, 1998; Stumpf & McDonnell, 2002). Others build on Schön's position to develop models or frameworks for describing the design process (e.g. Dorst, 1997) and to develop methodological approaches to support the actual performance of design (e.g. McDonnell et al., 2004). These studies draw on Schön to develop insights around the team design processes and communication (e.g. Stumpf, 2001; McDonnell et al., 2004), patterns of design team behaviour (Valkenburg & Dorst, 1998), the enactment of team thinking (Dong et al., 2013), and the use of different media in design team work (Gao & Kvan, 2004; Rahimian & Ibrahim, 2011; Rahimian et al., 2011).

Both limitations and advantages of mobilising Schön's approach can be seen in this literature. Dorst (1997) comments on challenges of using Schön's view in studying design, and indicates 'reflective practice' in the first form developed by Schön (1983) as a primer for a new theory (i.e. different from technical rationality), and therefore configured as "rather sketchy…and with uses…not totally clear" (Dorst, 1997:73). Nevertheless, these studies do not obscure the advantage brought by Schön's reflective practice for supporting "a description of design activities that corresponds closely to design activities as they are experienced by its practitioners", a description that appears intuitively appealing to designers (Dorst,1997: 68). As highlighted by Dorst (1997), the potential of Schön's position to link theory and practice, and to provide an approach for accessing and enabling descriptions of design "as experienced by designers" , is a quality which has been substantially addressed and developed in subsequent work, as well as in Schön's own later studies. With regard to advantages brought by drawing on Schön's position, the above studies highlight capabilities of the theory of reflective practice to access valuable insights around design processes as experienced by designers and in relation to the context, in an enriched way than possible through other paradigms, such as treating design as problem-solving process. They stress the connection between Schön's type of understanding of the process with the designers' perception of their own practice (e.g. Dorst & Dijkhuis, 1995; Stumpf, 2001). Overall, this literature points toward the potential of adopting Schön's view on design as reflective practice as way to access insights around a variety of aspects regarding the social, material and perceptual processes involved in the ongoing accomplishment of design activities in situ.

Mobilising Schön's approach in this study

As discussed above, the use of CAVE technology for performing design work is examined in this paper from the position of seeing design as reflective practice. The choice of adopting Schön's theoretical understanding of design as reflective practice draws on the relevance to the concern of this study, around the actual impact of immersive technology on practices of design and the effect of CAVE on design work as used in concrete 'real-life' settings and as perceived by the practitioners involved. As argued above, Schön's approach on design as reflective practice is indicated as the approach to understand and describe the process in the closest way to how it is experienced and perceived by practitioners themselves. Moreover, this position of seeing design practice as a situated activity, emphasising the interactional aspects and the role of the materials, is consistent with the empirical work in this study, which draws on observing and recording people in naturally occurring situations of practice.

Contextualising Schön's work in the broader literature indicates a wide range of seminal design studies which connect with ideas of reflective practice, considering design less as a scientific type of process, but as practical accomplishment. This is realised through ongoing iteration of thinking and acting mediated through reflection. There are similarities between more recent literature and Schön's view not least in stressing the influence of Schön's approach in the design research community by marking the shift from the previously dominant positivist perspective on design as symbolic information processing.

However, often these studies building on Schön's work take a different interpretation of Schön's view to that adopted in this paper. The more specific ways in which these studies draw on Schön's work reflect their particular perspectives on design and support addressing their specific research concerns. As such, the design cognition research community (e.g. Lawson, 1997, 2004; Cross, 2001b; Dorst & Cross, 2001; Dong et al., 2013) highlights the more cognitive side of the process by drawing particular emphasis on the design thinking, perhaps in detriment of showing the same attention to the actions involved- the doing accompanying the thinking[1]. From approaches relating with behaviourally based cognitive psychology, this work draws mainly

[1] Schön's position on design as reflective practice treats cognition in the sense of inquiry, on Dewey's line (1938), as a "combination of mental reasoning and action in the world" (Schön, 1992:121). Differently than the design cognition research community, Schön's approach opens the door for design as practice, by turning the focus on how designers work: "In order to study reflection-in-action we must observe someone engaged in action."(Schön, 1983:322). Although some argue that "despite his emphasis on practice and experience, Schön's work is bounded by a certain cognitivist orientation" (Yanow & Tsoukas, 2009:1343), there is a big difference between the classical cognitivist approach to design and Schön's perspective (Schön, 1983; Schön & Wiggins, 1992) on design thinking as not contemplative, but active, by stressing the inseparability between thinking and doing in social interaction with the materials. As noted by Eastman (2001:151, 167-169, 184), Schön's work marks the shift from the classical cognitive models of design assumption on the location of design thinking in the designer's head (e.g. Lawson, 1997). Eastman also indicates Schön's description of the process as very different than the other protocol studies of design (the design cognition tradition of studies) by revealing insights in the dynamics of the process, and points out that Schön's analytical interpretation seems to correspond closely with what designers themselves think they are doing.

on experimental studies conducted in artificially restricted conditions. Also, this strand of studies focused on the design thinking tends to generalise, for example through developing theoretical models, design methods and methodologies, and neglect the situated character and the context dependency of designing.

Distinct from these design cognition studies, this paper is not aiming to generalize, but to understand design as a situated phenomenon, and it is not doing experimental research and it is not focusing on the cognitive side and individual cognition aspects of the process. Schön's empirical research is mainly based on cases involving novices/ students engaged in quasi-experimental situations, rather than professionals performing actual design practice. Acknowledging this aspect, this paper differentiates between Schön's theoretical view and empirical work, and draws on Schön's conceptual understanding of design as reflective practice to focus on the social phenomenon of interacting with the immersive technology by looking at what a group of participants do in order to perform their practice in the CAVE design situation.

By focusing on the accomplishment of design work in practice, this paper resonates with the strand of studies of design as practice (e.g. Ewenstein & Whyte, 2007; Luck, 2012). From a different perspective than the design cognition research community, these studies draw attention on the doing and reasoning involved in design as it is practiced, and turn more specific focus on the naturally occurring design interaction. However, although indicating their relation with Schön's position on design, these studies do not mobilise a reflective practice perspective, but build on other theoretical approaches and methodological commitments like, for example, organisational and aesthetics research perspectives, participatory design, ethnomethodology and conversation analysis. This study adopts Schön's ideas of reflective practice to focus on how the representations, models and technology are used and bound up in the process in a particular, specific context. Emphasising the situatedness, the interactional aspects and the role of the materials, this study employs video-based studies methods as way of mobilising the research.

In summary, this study draws on Schön's position around understanding design as realised in 'reflective conversation with a design situation' in concrete instances of practice, pointing to the contribution of particular people, representations and technology, and their inter-relationships in configuring the process through ongoing action. This literature review discussed Schön's position on design as reflective practice, acquainted his terminologies and highlighted the concepts taken forward in this research to examine how a group of design participants use a CAVE technology in a real-life empirical situation. This study mobilises Schön's ideas of design as situated, social and interactional practice-highlighting the perceptual, collaborative, communicative aspects, the role of the materials, the idea of design as conversation with the situation, and the more specific concepts of reflective practice -surprise, repertoires, appreciations, reflection-in-action, feel for the situation. In short, this refers to considering the cyclic, iterative process of reflecting and doing to address and engage with the particular design situation, and to respond to the elements of surprise by mobilising appreciations drawn on existing repertoires through both individual and collective reflection and action in conversation with the materials.

The study is also drawing attention to the movement between doing and reflecting, as well as between individual and collective reflection. At the same time, it is acknowledged that the empirical data may reveal a more fuzzy type of process, with more in-depth interlace between the phases and modes implied by Schön's model. This raises empirical questions around how traceable are the steps of the process according to Schön's model.

RESEARCH METHODOLOGY

This paper addresses the concern with understanding the effect of immersive technology on construction design activities as used in concrete 'real-life' design settings and as perceived by practitioners by drawing on and mobilising Schön's (e.g. 1983) ideas of design as 'reflective practice to examining the social phenomenon of interacting with such a technology in a particular situation of practice.

Schön's idea of reflective practice was developed, and explicitly positioned by Schön, as a counter to a more technical, instrumental, or objective approach to understanding professional knowledge and social practices. On this line of argument emphasising the inseparability between theory and practice, the design knowledge is in the action, in practice, and not a rigid application of science. It is not a process of following prescriptive rules, but of making sense of the unpredictable, messy, conflicting situations of practice and developing new understanding through experience in the situation. Schön' view argues that the design process can be understood through "close examination of what (…) practitioners actually do" within "unique, uncertain, and conflicted situations of practice" (Schön, 1983: viii- ix). Stressing the uniqueness of the design situations in practice, Schön's (1983) approach argues for an 'epistemology' of design as "reflective practice", idea which connects with adopting a strategy of inquiry through "reflection on the actual practice of (…) practitioners who reflect in action" (Schön, 1983:133). This research choice refers to understanding the design phenomenon through examining the practice, the actual performance of design, and to treat the actions whereby design participants perform the process as implicit to answering the research inquiry (Schön, 1983:49, 133). This approach points to accessing the dynamics of the phenomenon through examining how particular design participants think and work with representations, using technology and interacting with people in particular design settings. Consistently with the approach on design as reflective practice, the process can be understood by examining the practice through looking at what practitioners actually do in particular design situations: "A close look at a small, homely example of designing, in the narrower sense, will give us a parable of design practice" (Schön, 1992:127).

Drawing on this methodological approach, this paper operationalises the research through examining an empirical case of real-life design process performed using a CAVE. In line with the methodological principles set from the broader position of the study, the research mobilises direct observation and video-based research methods. The rational for choosing this approach builds on the consistency between the methodological principles of video-based studies – prioritising the situated and interactional accomplishment of practical action (Heath et al., 2010) - and the broad position of the study of conceptualising design as situated practice. Augmenting direct observation with video recordings draws on the tenets of video-based studies of workplaces and of interactions (Heath & Luff, 2008; Heath et al., 2010), which recognise and emphasise the potential of using video for examining how the interplay between the talk, visible conduct and the use of artefacts becomes relevant to the accomplishment of a social activity. This standpoint stresses practical advantages in mobilising video in research to investigate the ways in which the participants of interactions such as design meetings perform their actions on reviewing the design, to explore the interplay of their interactions with and around the technology, and to examine how they orient themselves to the technology and to other participants' actions. Rather than just employing direct observation, video recording brings the practical value of capturing gestures and movements alongside the verbal interaction as well as the ability to 'replay' the data during analysis. Although not commonly practiced, there is a methodological congruence between Schön's concept of reflective practice and video-based techniques in capturing the detail of design interactions.

The case study was based on an on-going project for designing a new hospital in the UK. One of the requirements is that all patient accommodation is in single rooms, rather than traditional multi-bed wards. Single room only accommodation is rare in the UK, and so a key issue for the client was ensuring that the rooms were of sufficient size, and that visibility into rooms was adequate. At the time of the research, the project was still in tender preparation stage. The project team opted to augment traditional design and client engagement activities with the use of a CAVE - a full scale 3D immersive environment set up in a UK University lab. This was to be used to demonstrate room size and show accurate lines of sight.

As particular type of immersive environment, the CAVE (Cave Automatic Virtual Environment) is a multi-person, room- sized, high-resolution multi-display 3D video and audio environment, in which graphics are projected onto the walls and the floor producing a fully immersive, true scale rendition. It offers the user (equipped with 3D stereo glasses and a head mounted tracking device with location sensor) active real-time interaction with a life sized 3D model. One user's movement in the space of the CAVE is being tracked and, consequently, perspective rendering is displayed responding to their position and movements (i.e. looking up or down). CAVE participants are fully within the space and can easily interact between themselves during the simulation (De Fanti et al., 2011). The CAVE at the University of Reading has three vertical projection screens (3m by 2.2 m) and a floor projection screen (3m by 3m).

The research used video recording and direct observation of a series of six sessions held within the CAVE, involving project and design managers, architects and designers, and modellers and visualizers, in various combinations. These were spread across five months, between November 2011 and March 2012. These sessions produced approximately 12 hours of audio-video recordings. Various combinations of video cameras were used to capture the design meetings: one hand-held camera, a second camera fixed on a tripod, positioned in one corner of the CAVE and a third camera fixed on the CAVE's ceiling to offer an aerial top down view. Conducting the research followed the University's ethical procedures regarding the participants' consent and the confidentiality and data protection.

ANALYSING REFLECTIVE PRACTICE IN THE CAVE

The analysis below discusses insights around the design process occurring in the CAVE, the activity around presenting the models to the NHS client and their use in demonstrating particular design requirements, and more generally around how the project teams are exploring the CAVE as a work setting. It is specifically concerned with examining how performing design reviews in the immersive environment are accomplished through situated interaction with a focus on understanding how the representations, models and technology mediate the process. Initial analysis of the video data let to the emergence of four tentative themes:

- orienting to the technology / situation;
- orienting to the design;
- thinking about the use and users of the designed space;
- representing the design to the client.

For the purposes of this paper, one approximately two minute vignette from the data set is used to unpack and demonstrate these themes and trace the relevance of Schön's insights on design practice.

A fragment of the empirical material

The video fragment below is extracted from the first of the six sessions reviewing the design in the CAVE, and refers to how the architects and contractors teams first encounter the immersive environment and perform a walkthrough of the virtual model of the hospital. This design event occurs in the first part of a one hour review session, and the interactions captured unfold between approximately minute 9 and minute 11 of this first design meeting held within the CAVE. It depicts a sequence when the project teams experience their first visit in the CAVE. The vignette is preceded by a general presentation around the technology, verbally introduced by the CAVE technical staff members. Following this, the design participants start their familiarisation with the immersive environment by removing their shoes (to protect the sensitive floor projection area), equip themselves with the 3D glasses and the head tracker, and begin to examine the state of the model in the main atrium area, in a joystick navigated simulation mode. In this stage of reviewing the design, the participants express a particular interest around the representational aspect of the CAVE rendering of the 3D model, and with how their design meets the client's requirements.

Designer 2 (09:07): ((…)) Just back (.) Can we have back a view from the reception area?
(09:08): There! ((pointing upwards to the right side of the displayed model))
(09:10): Just go back (.) a little bit left (.1) There! ((pointing to the left))
(09:12): We need to cut that back (.2) ((pointing))
(09:15): ((because)) You can't see through the concourse (.) if you're sitting on those chairs ((in the atrium))
(09:17): ((Designer 1 is leaning towards left))
Designer 1 (09:19): So: (.) That wall? ((pointing towards her left hand side))=
Designer 2 = Yes (.) There!
Designer 1 (09:21): Yea:h (.) Absolutely.
(09:23): ((towards Designer 3)) Can you check that back ((in the office))?
Designer 3 (09:25): Yeah (.2) ((making a hand note))
(09.27): I'm not sure why (.2) I thought that it was open view ((the perspective towards the concourse))
Designer 1 (09:30): Well that's ok (.) Yeah, that's the point of looking in a 3D environment (.) To see what we're actually doing!
Designer 1 (10.00): And this door (.1) it should be glazed! So you would see daylight coming through!
Designer 4 (10:10): It sounds good (.) I think we should capture as much detail as we can.

((The team discusses with the CAVE technician around the possibilities of refining the CAVE rendering of the design to increase the realism of the simulation))

Designer 4 (10:45): That's good (.) It's impressive cause (.1) This is quite good (.) cause showing this perspective is something you can't work out in any other way!
(10:48): To look (.1) ((points upwards to the right side of the model))
To see (.) upwards ((pointing to indicate the view of the atrium from ground floor up to the first floor through to the glazed curve shaped roof))

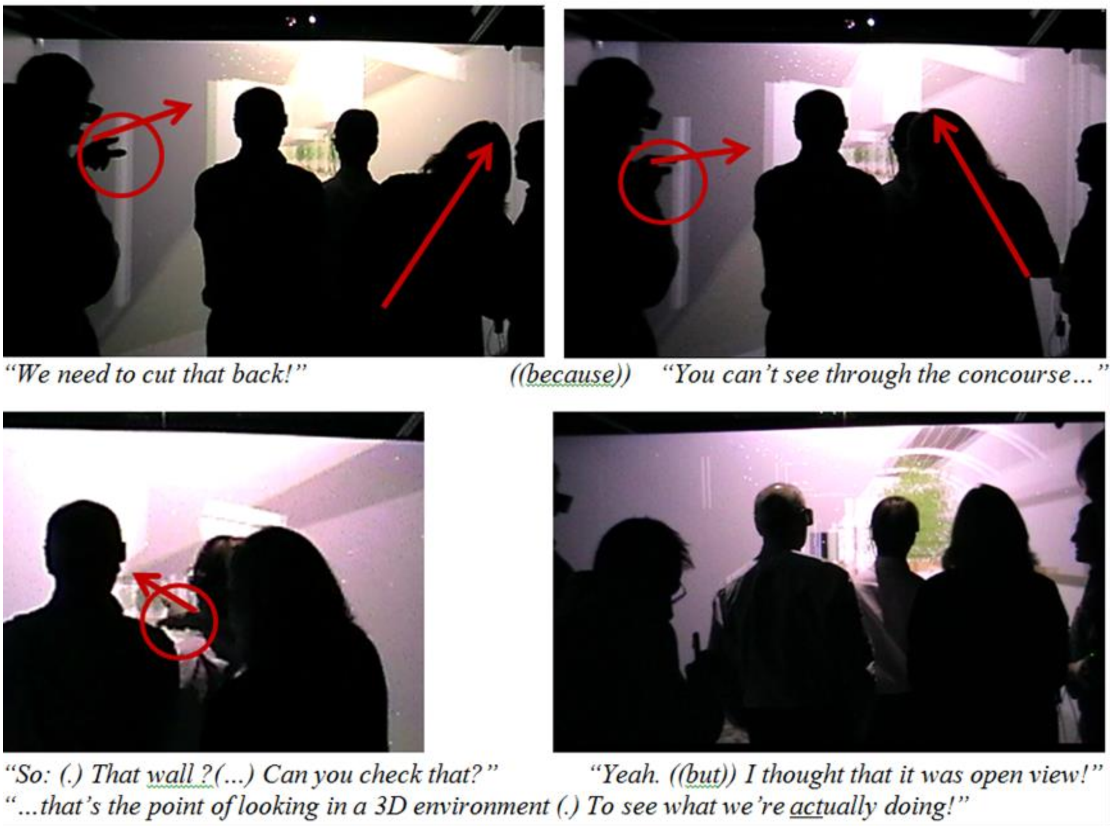

Figure 1. Episode 1 (E1, 09:12-09:30)

CAVE technician	(11:00):	If you get down, actually you can see a bit better
	(11:01):	((The contractor wearing the head trackers starts lowering down his body towards a kneeling position))
	(11:05):	((General loud laughing from the other participants))
Designer 4	(11:05):	You don't have to! ((leaning down and extending his arm to support the kneeling contractor))
	(11:06):	((General laugh continues))

((The viewing perspective of the model changes, offering a more ascendant image towards the roof from the eye level of a person sitting down on a chair))

Contractor	(11:22):	So if you move through, you can see what's there! ((gradually standing up))
CAVE technician	(11:24):	Yeah.
Designer 2	(11:28):	If we wanted to model daylight coming through that space, can we see it?
CAVE technician	(11:29):	Yeah (.) you can do that ((…)) but would be easier to model scenes of clouds, or blue sky (…)

"(...) this perspective (...) you can't work out in any other way!"

"If you get down (...) you can see a bit better"

"If you get down (...) you can see a bit better"

"You don't have to!"

"So if you move through, you can see what's there!"

Figure 2. Episode 1 (E1, 10:45-11:22)

Exploring the situation

In the moments preceding the interactions in the fragment presented above, the design and contractor teams were focusing on aspects of visual quality of the representation of the 3D model in the CAVE. The meeting was organized around the participants' discussion with the CAVE technical staff members around the technology, in terms of capabilities and limitations of the immersive environment, particularly with regard to displaying lighting and shadows, and materials and materiality (textures, colours, mapping) in the CAVE rendering.

Orienting to the design and to the technology (E1, 09:07- 09:10)

"Just back! Can we have back a view from the reception area?"

Starting with the instance opening this episode (E1), the design review process is disrupted by the reaction of Designer 2 towards a spontaneously perceived misfit in the design of the reception area: "Just back! Can we have back a view from the reception area?". Although the broader concern of the meeting was around the visualisation features of the CAVE representation, the simulation of the hospital building triggers Designer 2's attention on the state of the design scheme. Noticing an unexpected issue about the design, the participant asks the CAVE technician (who is navigating the model by joystick) to shift the visualisation of the model in an area previously displayed, and engages the other team members to re-examine the design of the atrium. The misfit regards the lack of confirming one of the design requirements in the model, more specifically the issue of enabling visibility from the reception area towards the two levels open space of the atrium, up to the transparent curve shaped roof.

Orienting to the design by accounting for the use and users (E1, 09:12- 09:21)
"You can't see through the concourse …if you're sitting on those chairs"

Moreover, this lack of conformity between the form and function of their design (the limitation of the scheme in terms of meeting the requirements) is considered with regard to the use of the design as real building, from the perspective of the future users: "You can't see through the concourse …if you're sitting on those chairs" ((in the atrium)).

This episode of discovering the design clash consequently triggers their decision on applying further changes to the design by removing the wall that was blocking the visibility:

"We need to cut that back "

This intention of changing the design formulated by Designer 2 is subsequently confirmed by other team members ("Yeah"; "Absolutely") through a series of group interactions around establishing a shared understanding of the model in the CAVE.

In Schön's terms, noticing the unexpected non-conformity of the model with the client's requirement is an element of surprise perceived in the design, surprise which triggers the designer's reflection on the situation with regard to changing the scheme. The instance denotes also a circumstance of moving, as a formulation and realisation of a design intention in response to the feedback of the representation. This sequence unfolds through a process of collaborative reflection-in-action whereby the participants manage to make sense together of the design, and to establish a shared understanding and group decision around further developing the design, with regard to addressing the discussed area of the interior space of the hospital. This is realised through the participants' orientation to both the design, and also to the technological setting, through a series of actions configured by interplaying verbal and bodily interactions among each other and with the display of the design (as captured in Fig.1), and whereby members of contractor and design teams align their vision as a group.

Moving between orienting to the technology and to the design (E1, 09:08- 09:21)
"There!" (…) "Just go back …a little bit left … There!" (…) "So: That wall?"

This process is collaboratively accomplished through firstly identifying the element blocking the visibility among multiple participants, each having different viewing perspective and hence different perception of the projection of the 3D model. This is due to their various locations in the space of the CAVE. The sequence denotes partly their reflection on the others' understandings, and partly how, for addressing this constraint in visualising the model in the same way in the CAVE, the group employs a set of situated interactions of orienting to the technology. This process is mediated through both verbal and bodily behaviour whereby the participants develop a shared vision on the design: between the moments E1, 09:08 and E1, 09:21 the review process is supported by the concerted actions of Designer 2, Designer 1 and the Cave technician. These interactions are expressed through verbal indications –like, for example, "There"; "A bit to the left"-, gestures -like pointing and arm movements to indicate the element-, multiple changes of gaze, or adjustments of bodily position, orientation or height (such as in the sequences below).

"There!" ((pointing upwards to the right side of the displayed model))
"Just go back …a little bit left … There!" ((pointing to the left))
"So: That wall?" ((pointing towards her left hand side))
"Yes (.) There!"

Figure 3. Episode 1 (E1, 09:08-09:19)

The data above exemplify the interplay of verbal with non-verbal interactions within making sense of the design situation in the CAVE: Designer 1 shifts her body orientation from leaning towards the right to the left side of the CAVE. Concurring to the situation, the Cave technician orients the joystick navigation of the model according to the verbal and bodily indications of Designer 2. The sequence illustrates the participants' processes of addressing the design situation through iteratively orienting to the technology and shaping an understanding of the CAVE rendering of the model and of the scheme.

Also, the sequence infers a process of moving between making sense of and engaging in conversation with the design situation in the CAVE. The participants iterate between orienting to the unfamiliar technological setting, making sense of the CAVE version of the design, and in response to the understandings gradually developed around the current state of the design, drawing collaborative decisions regarding further changes to the scheme and refinement of the representation.

Orienting to the design and representing: changing the design (E1, 09:12- 09:25)
"We need to cut that back!"

Designer 2	(09:12):	We need to cut that back (.2) ((pointing))
	(09:15):	((because)) You can't see through the concourse (.) if you're sitting on those chairs ((in the atrium))
	(09:17):	((Designer 1 is leaning towards left))
Designer 1	(09:19):	So: (.) That wall? ((pointing towards her left hand side))=
Designer 2		= Yes (.) There!
Designer 1	(09:21):	Yea:h (.) Absolutely.

These interactions immediately following the previous sequence in the episode reveal an emerging movement from the participants' shared understanding of the model to addressing the situation by formulating the intention of changing the design : "We need to cut that back!" (Designer 2) and establishing the group agreement around the decision of changing the design - "Absolutely!". Consequently, between the moments E1, 9:23 and E1, 09:25, the flow of this process of orienting to their design leads the participants to move from understanding the model and deciding changes of removing the wall blocking the visibility towards the atrium to making steps towards actually materialising this decision. This is realised through collaborative interaction between Designer 1 and Designer 3 around further applying the established intervention on the design outside the CAVE, in the architects' offices. The interaction is verbally expressed by Designer 1- "Can you check that back?" and followed by the confirmation "Yeah" of Designer 3 who is also marking a hand-note about the design change in his notebook.

Figure 4. Episode 1 (E1, 09:25)

In Schön's perspective, the sequence may be referred to as moving from formulation of intention to realising the intention of changing the design situation. Also, the sequence already marks a shift from using the CAVE in the review process not only as a presentation tool, but also as a medium which contributes by enriching the designers' understanding and informing the further development of the scheme itself.

Orienting to the design: not confirming expectations (E1, 09:27)

"I'm not sure why … I thought that it was open view"

The previous sequence is immediately accompanied by the Designer 3's reflection on the design scheme, on the representation and on the medium: "I'm not sure why … I thought that it was open view". The Designer 3's reaction restates the surprise perceived around the clashing element in the design and infers that drawing on his previous experience of visualising the model (on paper, Revit on a computer screen) his assumption was that the visibility requirement towards the concourse had already been addressed in the design. In Schön's vocabulary, the sequence infers that the design element blocking the visibility in the atrium is perceived as unexpected from Designer 3's appreciation system, drawing on his repertoire of understanding. Also, from a 'reflective practice' perspective, the sequence exhibits a circumstance in which the feedback of the representation reveals a lack of conformity with the design expectations, and consequently triggers reflection on the previous and current actions, understandings, media and procedures, accompanied by generating new meanings and employing new action to address the situation in a different way.

Orienting to the technology (E1, 09:30)

"(…) that's the point of looking in a 3D environment (…) To see what we're actually doing!"

These interactions of orienting to the design, are entangled subsequently with Designer 1's reflection on the use of the medium to support design practice: "…that's the point of looking in a 3D environment …To see what we're actually doing!". The designer expresses an awareness developed around how visualising and experiencing the model in the CAVE supports the designers' collaborative appreciation of the outcome of former design intentions, and enables the project teams to notice issues about the design which were unexpected from previous representations. Interestingly, the last aspect indicates a circumstance in which the process of orienting to the design in the CAVE environment is challenging previous understanding drawn on the usual design procedures based on using other types representations and technology.

Representing the design: drawing attention to the detail (E1, 10:00- 10:45)

"(…) I think we should capture as much detail as we can"

Further in the episode, Designer 3's reflection on the role of the media for revealing issues about the design triggers drawing attention to the level of detail of the representation in the CAVE:

"And this door should be glazed! So you would see daylight coming through!" (E1, 10:00).

The moment marks a circumstance of orienting to the design by noticing another unconformity with the requirements - the door should be transparent - from the concern with the experience of the space by potential users -"you would see daylight". It is a transition in the focus of the meeting from understanding the scheme to starting to think about more detailed representational aspects. Consequently, the design participants shift the focus of the meeting to the potential of using the CAVE for enhancing the representation. A fourth participant, Designer 4 finds the idea of actually seeing daylight through the particular window in the CAVE simulation of the model as a useful detail for providing a real like experience of the virtual design. This instance triggers the participants' attention to thinking about representing the design for the client: "It sounds good. I think we should capture as much detail as we can" (E1, 10:10). Subsequently in the sequence, the team discusses with the CAVE technician around the possibilities of refining the CAVE rendering of the design for increasing the realism of the simulation.

Orienting to the technology (E1, 10:45- 10:48)
"It's impressive (…) cause showing this perspective is something you can't work out in any other way"

Following this, the participants move again to thinking about the potential of the particular immersive environment to support the review process in ways not possible using other types of design media: "It's impressive…cause showing this perspective is something you can't work out in any other way" (E1, 10:45). Designer 4's reflection expands on the initial familiarisation with the ways of navigating the model in the CAVE, by moving towards exploring the potential of the medium to support their process going forward. Building up an understanding of the technology, the participants suggest advantages of the CAVE through enabling an immersive experience of being inside the life size scale virtual model of the design with own physical body: "…to look..((panoramically)) … to see upwards!". "It's impressive ((…)) cause showing this perspective is something you can't work out in any other way! To look ((points upwards to the right side of the model)) To see (.) upwards"

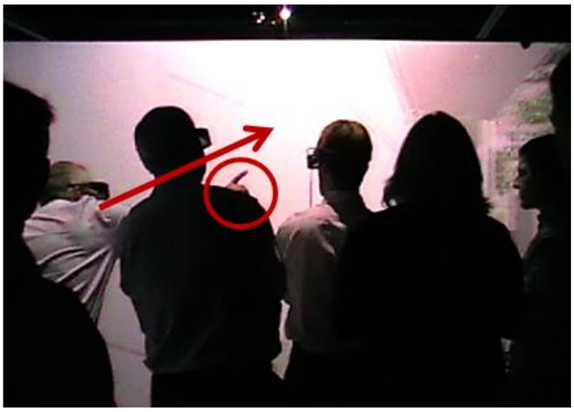
Figure 5. Episode 1 (E1, 10:45- 10:48)

Throughout their process of gradually familiarising themselves with the CAVE technology in the course of the review session, the participants are shaping an understanding around the potential of using the immersive setting for performing design. This type of process illustrates what in Schön's vocabulary might be referred to as developing a "workable understanding" (Schön, 1992:126), or a 'feel for' the design situation and for the medium. These aspects are observable in how, starting the moment E1, 11:00, they begin to orient to the technology through exploring the type of experiencing and the ways of understanding the virtual model in the CAVE. The design participants' familiarisation with the technology earlier described is mainly drawn on verbal introduction around the technology from the CAVE technical staff around informing them about particularities of using the CAVE, such as taking off the shoes for protecting the floor projection area, equipping with the head trackers and special 3D glasses to achieve stereo view and active navigation. In the beginning of the episode, although one of the participants is already wearing the head tracker, the navigation is still lead by joystick by the CAVE technician who simulates the model through the key areas in the model according to verbal guidance of the project teams. But here they are beginning to explore the possibilities of the model, moving beyond their initial orientation.

Orienting to the technology: making sense of the potential of the technology in use
"If you get down, actually you can see a bit better" (E1, 11:00- 11:05)

Starting the instance E1, 11:00, when the Contractor wearing the head tracker is actually kneeling to test the CAVE technician's suggestion of getting lower to then look up, the participants begin to make sense of the capability of the CAVE to enable a more dynamic simulation of the walkthrough, and recognise their own body movements in responsive interaction with the virtual model. The sequence exhibits rich verbal and bodily behaviour of the participants. They note how, in response to the Contractor's body movement and change of height, the images of the rendering displayed on the projection screen change accordingly, offering a more ascendant view towards the roof of the atrium from the eye level of a person sitting down on a chair in the reception area. This whole episode is accompanied by a general tone of amusement, marked by loud laughing within the teams' members, and by the reaction of one participant (Designer 4) to spontaneously initiate a gesture of trying to help the Contractor get back to a standing position. This is expressed by Designer 4 through the verbal utterance "You don't have to!", augmented by a bodily behaviour of leaning down towards the kneeling Contractor and extends his arm to support him.

"If you get down, actually you can see a bit better"

"You don't have to!"

"So if you move through, you can see what's there!"

Figure 6. Episode 1 (E1, 11:00- 11:12)

This reaction indicates how the group perceives the particular type of interaction with the technology and with the model in a design meeting as different and unexpected. The event denotes the surprise perceived around the unfamiliar way of experiencing a 3D simulation of design, which is new to them. The sequence reveals a particular type of social interaction emerging within performing design review in the CAVE environment, both in terms of a sense of fun and excitement, and through bringing a range of non-verbal means of interacting among group members.

This connects with a process of orienting to, or making sense of the use of technology, an aspect which in Schön's vocabulary is developing "workable understanding" (Schön, 1992:126), or a feel for the medium and for the ways of doing design in the CAVE, through shaping a group understanding around the potential of the immersive environment. The fragment displays how the participants develop a feel for the possibilities of enhancing the representation and the CAVE experience of the design for impressing the client. This gradual process of orienting to the technology is observable in the sequential movement from "…you would see daylight coming through" (E1, 10:00), to "It sounds good (.) I think we should capture as much detail as we can." (E1, 10:10); "That's good (.) It's impressive cause … showing this perspective is something you can't work out in any other way!"; "to see upwards" (E1,10:45), and then, towards the final part of the fragment, to thinking about modelling daylight to show it in the CAVE simulation (E1, 11:28, 11:29), and so on. The data conveys a sense of the continuity and flow of this situated process, realised through iteration between episodes of orienting to the technology, making sense of the design and thinking about further developing the scheme and the model, and about representing it for the client.

DISCUSSION AND CONTRIBUTIONS

From the analysis, four themes or sets of activities can be identified. There is initially some collaborative effort made to make sense of this novel environment and to establish what it can do, for instance in the conversations with the technician around levels of detail or the function of the head-tracker (e.g. E1, 09:07- 09:10, or E1, 11:00- 11:29). This is orienting to the CAVE technology. Simultaneously, the participants are collectively making sense of the representation of the design within the environment (e.g. E1, 09:07-09:30), through asking for different viewpoints (E1, 09:07-09:10), moving around the space (e.g. E1, 11:00-11:22) and noticing aspects of the design they did not expect from their prior understanding of it. For example, by simulating the model in the CAVE, the participants discover that their design scheme is not complying with the client requirement around the visibility towards the reception area (E1, 09:15). This is perceived as surprising because it is not confirming their expectations drawn from previous visualisations of the design- REVIT on screen (E1, 09:27). The surprising outcome is subsequently triggering the participants' decisions on further change the design (E1, 09:12). In this case they comment that the environment can show perspectives on the design that other media cannot (E1, 09:30, E1, 10:45-10:48). This can be seen as orienting to the specific design within the CAVE. Just a few seconds later, the team is not just discussing aspects of the design, but the perception of it from the point of view of users, such as rehearsing the view from the chairs in the atrium (E1, 09:15), or discussing the glazing in the door to increase the life-like nature of the model (E1, 10:10- 10:45). This is exploring alternatives for the use and users of the space. The discussions also go beyond the design brief and use to the way it can be demonstrated to the client, for instance in modelling the sky, clouds and external features (e.g. E1, 10:10- 10:45; or E1,11:28- 11:29). This can be seen as strategic interactions around how to best represent the design and model to the client.

Together, these four themes of 1, orienting to the CAVE technology itself, 2, orienting to the representation of the specific design within the CAVE, 3, activities accounting for, or exploring alternatives within the design for the use and users of the space, and 4, more strategic interactions around how to best represent the design and model to the client within the CAVE setting represent a pattern of engaging with design work in this immersive, novel environment.

The dynamics of reflective practice

The empirical material also illustrates that these four analytical themes overlap, even in a short fragment of two minutes of interaction. The findings indicate that the process of reviewing the design in the CAVE follows an iterative flow of orienting to the technology and to the design, thinking about the use/ users of the space, and representing out the design for showing it to their client. In line with Schön's perspective, this type of empirical process is revealing a pattern of reflective practice, through spiraling between discovering and designing, making sense of the situation and actively addressing it, in a flow of both shaping the situation and, in return, shaping the understandings and the subsequent actions.

Reflecting on the debate over the dynamics of reflective practice, the study confirms a tension between linearity versus a circularity of the process. The analysis of the video data identifies the steps by which the participants perform the process in situ through orienting to the technology, making sense of the design, actually doing design work, then thinking about the use and users, and about representing the design for engaging with the client. The thematic analysis shows that these steps can be identified and focused upon separately, but it also reveals a circularity and simultaneity or concurrence of these, in the entanglement by which these types of processes occur concomitantly, and without following a specific order. Relating back to the critique discussed above, the data shows exactly the fuzziness indicated by the studies criticising Schön. Drawing on the empirical findings, the study indicates that these thematic aspects are addressed both in distinct stages, and intertwined, revealing a complex, interdependent and iterative process in which making sense and design work are inseparable. Therefore the study confirms the tension around the linearity versus circularity of the design process and recognises this issue in the empirical data as a complex combination of processes.

Other insights to Schön's approach to understanding design practice

The study contributes to Schön's approach to understanding design practice by accounting for, and analysing in detail the non-verbal interaction through bringing together Schön's approach on design as reflective practice and a video-based studies approach as method for inquiry. The findings of this study reveal some unique aspects of design work in this immersive environment, that span across and beyond these analytical themes:

- The data suggests distinct social aspects of design behaviour emerging in the CAVE, especially with regard to the participants' excitement (amusement, episodes of laughing) in the environment.
- The physical and bodily presence of the design participants within the CAVE model is connected to a greater reflection on ways of using the space, and even simulating the roles and actions of end users.
- Performing design in the CAVE environment is enhancing or adding to an existing understanding of design through paper based or non-immersive digital representations, and perhaps most significantly, it is also challenging or surprising the participants as they experience the immersive, full scale version of their own design.

Overall, the findings of the study demonstrate the relevance of mobilising Schön's approach to design as situated, social, material, and perceptual practice, and the more specific concepts of reflective practice - surprise, repertoires, appreciations, reflection-in-action, feel for the situation- as a useful way of inquiring the use of the CAVE in performing design work. The study also demonstrates the utility of video-based data collection techniques for capturing the details of design interactions. Although this is not commonly used in design oriented studies, in this case it offered a useful and practical means to retain and replay the data, and potentially offers an alternative or supplementary method to further explore the contours of design practice.

The study enhances the existing understanding around the practical consequences of using CAVE's in design, and informing the development of the technology from a practice perspective. Distinctively, these contributions build on and extend prevailing work in the existing usability testing and technology development literature.

CONCLUSION

The aim of this study was to examine the use and the implications of immersive virtual reality technologies in the construction design process. This aim was addressed by taking an interest in the use and implications on the actual design practice and practitioners, and it was pursued through reflecting on the effect of immersive technologies on construction design activities as used in concrete 'real-life' settings and as perceived by the practitioners involved. Empirically, this broader aim was investigated by focusing on the use of CAVE technology in a real world design project, from a perspective stressing the participants' view on the role and utility of the technology in performing actual design work.

The central idea highlighted through the study points out that using the CAVE both mediated and bounded up in performing design work configured as social, collaborative and context dependent process. The study found that, moving beyond initial intention of using the technology as a better way to convince the client within the bid process, the participants used the CAVE for more than just presenting the design, but also for performing actual design work.

The study clearly identified a complex set of interactions emerging in the CAVE design process through the participants' iteration between collaboratively making sense of the technology, orienting to the design in this environment, and then doing further design work in consequence to perceiving new issues or finding out unexpected aspects about their design. Importantly, the CAVE design review experience did not only provide a better representation of the 3D model, in a more exciting design environment, and it did not only extend, but it also challenged participants' understandings of their design and their usual ways of working. The findings suggest that the immersion in the life-sized version of the 3D model, the feel of space, the physicality involved and the social aspect of designing in the CAVE, contributed to distinct ways of accomplishing design practice. Performing design in the CAVE was realised in a fundamentally social and interactive way, by making sense of the technology and of the CAVE representation of the design, interacting with the model and among participants, and then doing more design work. Using the CAVE for reviewing the design triggered changes to the design and affected the further development of the project and the engagement with the client.

Limitations and potential avenues for further research

There are limitations to all research. This research was limited to investigating a particular design phase (design review, part of the bid preparation) within a particular project. This empirical context enabled a close examination of the detailed interaction occurring in the design situation of the particular design episodes, but it would have been interesting to follow the use of the CAVE in other stages in the process, such as for early design. A potential avenue for further work might be to investigate how the CAVE would be used earlier in the process, where there is less certainty around the design, as well as later, in detailed design and construction phases. It might also be interesting to examine the use of the CAVE as design setting for developing other projects, involving other design teams, and to trace possible patterns of design interactions across multiple situations.

Capturing the video data encountered several technical limitations, particularly caused by the lighting issues in the CAVE, but also by the way of setting the video cameras. The study experimented various combinations of cameras- fixed on tripod placed in the corners of the CAVE, fixed mounted on the ceiling for aerial view, and mobile hand held cameras. Using more fixed cameras would allow better capturing the detail of gestures.

In relation to the findings around the surprise and challenge triggered by the use of the CAVE on designers' understandings and procedures, the study indicates that an interesting potential avenue for further work would be to examine the implications of integrating the CAVE within design usual work and procedures. Future research could examine how the practitioners would think about and use the CAVE if they would have the technology in their daily workspaces and how would this change the dynamics of their practice.

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UNDERSTANDING CREATIVE DESIGN PROCESSES BY INTEGRATING SKETCHING AND CAD MODELLING DESIGN ENVIRONMENTS
A Preliminary Protocol Result from Architectural Designers

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Abstract
This paper presents the results of a preliminary protocol study of the cognitive behaviour of architectural designers during the design process. The aim is to better understand the similarities and differences in cognitive behaviour using Sequential Mixed Media (SMM) and Alternative Mixed Media (AMM) approaches, and how switching between media may impact on design processes. Two participants with at least one-year's professional design experience and a Bachelor of Design degree, and competence in both sketching and computer-aid design (CAD) modelling participated in the study. Video recordings of participants working on different projects were coded using the Function-Behaviour-Structure (FBS) coding scheme. Participants were also interviewed and their explanations about their switching behaviours were categorised into three types: S→C, S/C⇆R and C→S. Preliminary results indicate that switching between media may influence how designers identify problems and develop solutions. In particular, two design issues were identified. These relate to the FBS coding scheme, where structure (S) and behaviour derived from structure (Bs), change to documentation (D) after switching from sketching to CAD modelling (S→C). These switches make it possible for designers to integrate both approaches into one design medium and facilitate their design processes in AMM design environments.

Keywords: *Creative design process, sketching, CAD modelling, cognitive behaviour, mixed media design environments.*

INTRODUCTION

Due to the increased globalisation of architecture, engineering and construction (AEC) projects, current research has shifted from individual design environments to the integration of different design environments to achieve better outcomes (Gouldinget al., 2014). According to a survey of 106 expert designers conducted by Romer et al. (2001), the two most frequently used design media in the design industry and design schools are sketching and computer-aided design (CAD) modelling. The integration of sketching and CAD modelling form mixed media design environments. In empirical studies conducted by Chen (2007) and Ibrahim and Rahimian (2011), designers were asked to initially use traditional sketching before shifting to CAD modelling. For the purpose of this research, this use of mixed media, in which one shift between media occurs with no backtracking allowed, is defined as Sequential Mixed Media (SMM). However, researchers (Do, 2005; Sachse et al., 2001) found that designers prefer to move freely between media, alternating at will between sketching and CAD modelling. This method is termed Alternative Mixed Media (AMM) and is a process frequently used by designers. Most of the understanding about cognitive behaviour in mixed media design environments is based on studies in SMM environments. However, there is little empirical evidence that supports a comprehensive understanding of cognitive behaviour in AMM design environments. Questions about the differences between SMM and AMM and whether switching between media impacts on the design process remain unanswered and are therefore important to explore.

To address these questions, a protocol study was conducted in which two professional architectural designers were asked to perform an architectural design task in SMM and AMM design environments. Protocol analysis and the Function-Behaviour-Structure (FBS) coding scheme were adopted and developed as the research method to analyse participants' cognitive behaviours. Preliminary results identify the cognitive changes that differentiate SMM from AMM as well as the impact of switches in design processes. These are discussed in this paper.

RELATED DESIGN STUDIES

Providing solutions that effectively meet the requirements of design briefs is the ultimate goal of designers. A creative design process is best defined by its output - creative design processes produce great design outcomes (Sobek II and Jain, 2004). Teaching students about creative design processes is a common goal of many architectural design courses worldwide. The earliest phase of the design process focuses on understanding the problem at hand and making decisions about solutions (Cross and Dorst, 1999). This phase, referred to as conceptual design, has a significant impact on detailed design, cost and construction. Some methodological studies about this phase, such as the synectics method (Gordon, 1961) and the brainstorming method (Osborn, 1963), highlight the importance of sketching or drawing to illustrate concepts. Sketching has been intensively studied in early architectural design, where individual designers begin to develop their conceptual designs for a building by sketching a plan, elevation, or a view of a building (Eckert et al., 2010) or by making unexpected discoveries about design problems (Suwa et al., 2000).

Research on sketching design environments

Sketching is used not only to communicate the results of architectural design to clients, users, legislators and constructors, but also as a central tool in the design process (Lawson, 2002). Sketching plays a pivotal role in the initiation and development of creative ideas during the early design phase. Designers rely on it to support and accentuate the visual reasoning necessary to explore the spatial relationships between diagrams. The design problem space evolves from an ill-defined problem to the identification and resolution of creative ideas when designers interact with sketches.

Sketching makes an important contribution to the design process. Initially designers brainstorm as many ideas as possible. Sketching is central to this process as raw sketches can be easily generated, revised, refined and consolidated as ideas are developed. Consequently, sketches act as a conceptual tool for designers, supporting and stimulating creative ideas (Goldschmidt et al., 1992). Suwa and Tversky (2001) argue that professional designers use sketching to generate new ideas, rather than to simply express current ideas. They observe that the simple process of re-examining old sketches, including one's own and others' can lead to unexpected discoveries that generate new ideas.

Although sketching offers flexibility, is quick and encourages intuitive interactions, making its use popular amongst designers in the early design phase (Gross and Do, 1996), sketching can interrupt the flow of the design process especially when designs need to be transferred to CAD. To readily transfer sketches into CAD, designers are increasingly using computer program applications like ArchiCAD in the early design stage. Furthermore, the increasing globalisation of projects in AEC has complicated design processes, rendering conventional sketching tools largely inadequate. Consequently, CAD modelling is increasingly being used in complex projects because it provides the additional benefit of digital representation and communication for future analyses and process integration.

Research on CAD design environments

The expressive and geometric power of CAD modelling has increased to such an extent that it can be used by itself from beginning to end to achieve design goals. This approach replaces traditional methods such as sketching and can be termed a digital design process. Although traditional sketching methods are low cost, 2D representations may not convey ideas about complex 3D objects. For example, sketches are imprecise when multiple 2D views are used to produce a 3D perspective. In a CAD modelling design environment, 3D graphics (e.g. perspective views) can be employed to generate and manipulate 3D geometry (Aish, 1986). CAD modelling can be meaningfully used to support problem-solving in the design process. Conventional approaches involve sketching as a means of representing basic conventions, but these are inadequate for solving complex problems (Lin, 2001).

More recently, CAD modelling has proved to be effective across the whole range of AEC practices. Designers and clients use CAD models to review and evaluate building designs before construction. This provides them with opportunities to make substantial changes at a reasonable cost. Engineers use CAD models to evaluate structural alternatives (Reffat, 2002). Industry professionals use CAD models to estimate costs and to plan for cost-effective construction sequences. These processes frequently unearth design conflicts that would otherwise result in expensive construction defects. For existing buildings it is often desirable to use CAD models to analyse energy properties, to explore how a potential fire could spread, to explore potential changes in a building, and to increase the possible uses of existing building spaces (Lewis and Sequin, 1998). Some argue that cost savings of at least 30% are possible if the design and construction industry commits itself to complete CAD modelling (BSS, 1997). Moreover, the accurate visualisations possible with CAD modeling may help designers to alter and refine their design thinking (Salman et al., 2014).

There are thus clear advantages to using CAD to support design processes, and researchers continue to seek ways to integrate sketching and CAD modelling into one design medium to improve the conceptual design phase.

Research on mixed media design environments

In recent years research has shifted from single design mediums to the influence of mixed media on cognitive activities during the conceptual design phase. Evidence for the use of mixed media comes from Sachse et al. (2001) who surveyed more than 100 expert designers who used sketching prior to and concurrently with CAD modelling. Their study identified three positive outcomes of this approach: better solutions, faster task completion, and fewer processing steps to develop CAD models. These results are supported by Chen (2007) who studied design creativity by using conventional and digital media simultaneously. The results showed that as designers switch from sketching to digital tools, design creativity is stimulated because switching behaviour causes designers to re-think previous ideas and to improve the quality of their designs.

Ibrahim and Rahimian (2011) argued that the CAD software available at the time did not facilitate the intuitive aspects of conceptual design. Therefore they introduced the concept of mixed media which is an integration of sketching and CAD modelling. They conducted a protocol study of architectural students in three discrete design environments, mixed media, sketching and CAD modelling, and found mixed media to be the most effective external representation tool because it generates higher quality solutions than either CAD modelling or sketching.

Interaction between sketching and CAD modelling encourages switching behaviour that may have the potential to impact on design processes. These mixed media studies underpin further research which compares cognitive behaviour in SMM and AMM design environments.

RESEARCH METHODOLOGY

The credibility of a study depends upon the research method chosen and the way in which the research is conducted. Different ways of using sketching and CAD modelling in design provide various benefits. Determining which methods were the most appropriate for the research questions of this study was challenging. Sketching and CAD modelling remains a natural design process and is considered to be a real phenomenon. A major difficulty in mixed media research is the methodological problem of identifying the function and properties of each method and the underlying operations in the cognitive study. Another major difficulty is that of identifying switching processes between the sketching and CAD modeling.

Different approaches have been taken to study designers (Cross, 2001) including interviews with expert designers (Cross, 1999; Cross and Cross, 1995), observations and case studies (Candy and Edmonds, 1996), stimulation trials (Gero and Sudweeks, 1998) and protocol studies (Akin 1993; Pour Rahimian et al., 2011; Suwa and Tversky 1997; Tang et al., 2011). Studying mixed media in design is more difficult than studying individual design environments (Kan and Gero, 2008; Suwa and Tversky, 1997; Tang et al., 2011). In addition, the SMM approach can easily be frustrated when switching between media is prohibited and there is no reliable method of analysing the impact of switching behaviour.

Protocol analysis offers a potentially effective method for the controlled observation and experimental analysis of cognitive behaviour (Akin 1993; Candy et al., 2006). Protocol analysis can be used to help understand the design process of designers, the knowledge they use, the cognitive actions they take and the strategies they employ. An application of protocol analysis is to ask designers how they design an artefact. However, they usually find this question difficult to answer in detail. This is because designers often store their design thinking in their short-term memory while designing. Another possibility is to look at their sketches, notes or CAD models, but without further information it is difficult to understand their design processes. Many studies (Akin 1986; Ibrahim and Rahimian 2011; Suwa and Tversky 1997; Tang et al., 2011) show that protocol analysis can record almost all information about designers' reasoning during the design process rather than simply relying on their design results for such insights.

There are two ways to report protocol data: retrospective and concurrent (think-aloud) verbailisation (Doorst and Dijkhuis, 1995). Generally, retrospective verbalisation means that designers perform tasks and are questioned afterwards about their thought processes during their design. Another approach is to video design sessions and to review recordings together with the designers enabling them to interpret what happened. However, it may be difficult to remember thought processes after an activity has been completed and the usefulness of this method is limited (Newell, 1990). Another problem is that designers may present their thought processes as more coherent and intelligent than they originally were; they may not report thoughts they actually had during the design process and may instead report false memories. This may give a false impression of perfectly rational behaviour (Newell, 1990). Designers' retrospection means that information must be retrieved from long-term memory and then verbalised. The disadvantage of this approach is that the retrieval process may not unearth all the information that was actually experienced in short-term memory during the design processes.

On the other hand, the think-aloud protocol requires designers to verbalise his / her thoughts while designing (Tang, 2001; Van Someren et al., 1994). In other words, designers explain their thoughts whilst performing the task at hand. Unlike retrospective protocols for gathering verbal data, no set questions are asked. Designers are encouraged to give a concurrent account of their thoughts and to avoid interpreting what they are doing (Gero and Tang, 2001). This method is more successful because almost all of a designer's conscious effort is aimed at achieving the design task. This restricts the opportunities for them to reflect on their design activities. As such, the data gathered are very direct; there is no delay that can result in altered data. The advantages of concurrent verbailisation fit the aim of this research because this process focuses on analysing actual designers' cognitive actions rather than using subjective self-reports (Salman et al., 2014). Therefore, concurrent verbalisation was selected for this study.

Generally, protocol studies involve the following steps (Ericsson and Simon, 1993; Kan and Gero, 2008): (1) Proposing a research direction/gap; (2) Participant recruitment and experiment set-up; (3) Conducting/recording the experiment; (4) Transcribing protocol data; (5) Development of a coding scheme; (6) Encoding the protocol data; (7) Analysis of the protocol data; and (8) Interpretation of results. The most important step is to propose an appropriate coding scheme that reveals meaningful research outcomes. The study reported here has two purposes; firstly, to explore whether the experimental design is effective in producing desired outcomes and, secondly, to test whether meaningful results emerge from the coding scheme. Depending on the preliminary results, the experimental design and the coding scheme may be revised. The next section introduces the FBS coding scheme and a justification for this study.

Justification of FBS coding scheme for mixed media design study

Gero's Function-Behaviour-Structure (FBS) framework was developed in 1990 (Gero, 1990) and has evolved over the last two decades. Many protocol design studies have adopted the FBS model to describe design processes and tasks (Gero and Kannengiesser, 2004). Some researchers argue that the definition of function has not been stable over the years and that the FBS model both describes actual designing and prescribes improved designing (Tang et al., 2011). Thus, the definition of FBS has been revised to encompass these nuances. The FBS coding scheme is defined as a process-oriented design theory in which designing is understood as a sequence of distinguishable stages.

The FBS coding scheme (Figure 1) situates designing in terms of six design issues: requirements, functions, expected behaviours, behaviours derived from structures, structures and documentation. The goal of designing is to transform a set of requirements (R) into a set of design documents (D). The function (F) of a designed object is defined as its purpose or teleology. The behaviour (B) of that object is how it achieves its functions and is either derived (Bs) or expected (Be) from the structure. The structure (S) comprises the elements of an object and their relationships. A design description is never transformed directly from the function but undergoes a series of design processes among the FBS design issues. These design processes include: a formulation (F→Be) which transforms functions into a set of expected behaviours; a synthesis (Be →S), wherein a structure is proposed that is likely to exhibit the expected behaviour; an analysis (S→Bs) of the structure which produces its derived behaviour; an evaluation process (Bs⇆Be) which acts between the expected behaviour and the behaviour derived from structure; and documentation (S→D), which produces the design description (Gero and Kannengiesser, 2004; Gero and McNeill, 1998). Depending on the structure, there are three types of reformulation, where new variables are introduced: reformulation of structure (S→S), reformulation of expected behaviour (S→Be), and reformulation of function (S →F). Reformulation of function is relatively rare, as it changes or redefines the design problem (Gero, 1990).

The FBS coding scheme has been used as a uniform framework to represent and classify design processes in numerous studies. A recent example compared the design processes of ten groups in a traditional sketching environment and in a digital sketching environment, encoding their protocol data using the FBS coding scheme. The transcribed protocol data needed to be divided into small segments to facilitate the coding process. Both the content of the segments and the transitions between segments in each environment were analysed statistically (Tang et al., 2011). The results revealed that the design processes used in digital and traditional environments were similar in terms of the speed of the design process and design issues involved. Moreover, Kan and Gero (2005) undertook a design study demonstrating that the FBS coding scheme can be used to compare different forms of collaborative design, such as face-to-face and virtual environments. They found two different processes of formulation and reformulation. The primary advantage of the FBS coding scheme is that it clearly shows the relationships between the eight design processes and the six design issues. It is an effective coding scheme for analysing design activities in SMM and AMM design sessions.

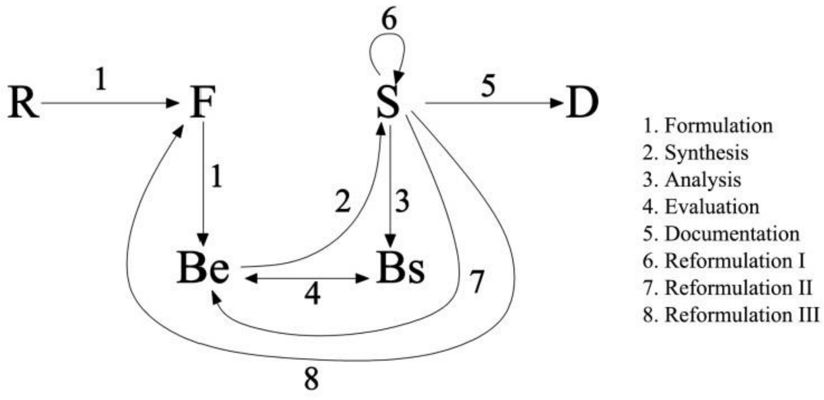


Figure 1. FBS coding scheme (Source: Gero and Kannengiesser, 2004)

Development of FBS coding scheme for mixed media design study

This study explored cognitive behaviour in mixed media design environments in contrast to other research (Bilda and Gero, 2006; Suwa and Tversky, 1997; Suwa et al., 2000) which studied cognitive behaviour in single design environments. Both sketching and CAD modelling facilitate design processes as external aids. A coding scheme structure was used to distinguish the cognitive behaviour in mixed media design environments (Figure 2). Based on the FBS coding scheme, both sketching and CAD modelling design environments consist of six design issues (R, F, Be, Bs, S, and D) to enable different distributions of design issues to be collected and analysed.

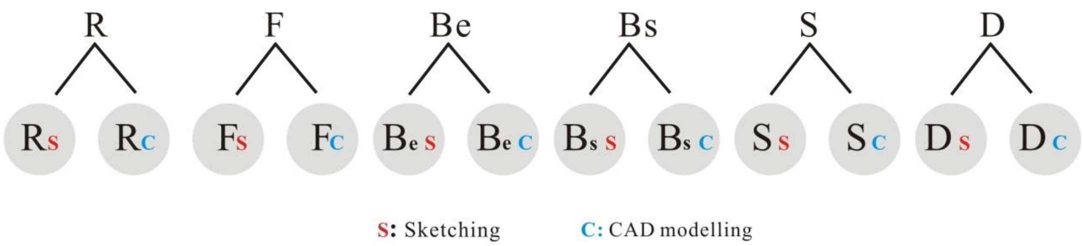


Figure 2. Development of FBS coding scheme for SMM and AMM sessions

This study provides a reference frame of the six design issues of the FBS coding scheme to calibrate the protocol segmentation and a coding process for SMM and AMM sessions (Table 1). Requirements (R) are usually imposed on design processes by external agents, like clients and regulations, rather than consciously by designers. In the study, the majority of the requirements were provided in the design brief and the site plan, presenting constraints not determined by the designers. However, designers consider other constraints in the process of producing their designs. As the function (F) refers to the purpose of design, the ‘function issues’ refer to a designer’s articulation of what a design brief requires, such as different functions of spaces and buildings. Behaviour (B) refers to what the artefact does and consists of expected behaviours (Be) and behaviours derived from structures (Bs). The distinction between Be and Bs is then made by examining whether a specific behaviour is the result of designers' expectations (future consequences) or a derived consequence from a structure (previous consequence). Structure (S) refers to an artifact defined as its components and their relationships, i.e. what the artifact consists of. Structure may also refer to physical features of the designed building, such as size, proportion, height, and material. Documentation (D) refers to external representations that designers use to express their thoughts, including writing or sketching on paper, and editing CAD models.

Table 1: Examples of using FBS coding scheme in mixed media environments

Design issues	Code	Example transcripts	Explanation
Requirement (R)	Rs	look at the template to see where I am (using sketching)	task requirement from original plan
	Rc	go back to design brief (using CAD modelling)	task requirement from design brief
Function (F)	Fs	kitchen can be kitchen again (using sketching)	designer's articulation of what design briefs want
	Fc	extend a wall between kitchen and meeting room for creating a small kitchen (using CAD modelling)	designer's articulation of what design briefs want
Behaviour (Be) and (Bs)	Bes	try evaluation of two offices (using sketching)	'try' suggests this behaviour is an expectation (Be)
	Bsc	light coming from north (examine a CAD model)	derived consequence from a structure (Bs)
Structure (S)	Ss	we can have a stair there (using sketching)	propose a component
	Sc	maybe distribute six pieces of glass (using CAD modelling)	refer to physical features
Documentation (D)	Ds	write down key words of design brief on the paper, reception area…for (using sketching)	documentation of Functions
	Dc	now I get rid of the roof (using CAD modelling)	editing CAD models

Designing the experiment

Protocol analysis can be used for a single designer, or a team of designers. Two architectural designers were recruited as participants in the study. They were initially identified from those who could best satisfy the selection criteria. To be included, the participants needed: (1) a tertiary degree in architecture with a minimum of one-year of professional architectural practical experience; (2) a design degree that had been obtained within the last three years so that participants had similar professional architectural practice experience; (3) competence in both sketching and CAD modelling; and (4) competence in practising and communicating design in English.

Another challenge in experimental settings is the development of an appropriate design task to achieve the research aims. Normally a 50 to 75 minute protocol task can produce sufficient data and a manageable protocol size (Dorst, 1996). Dorst (1996) proposed that design tasks be challenging, realistic, appropriate, not too large, feasible in the time available and within the scope of knowledge of the researchers. Architectural designers often design buildings and this study provided existing models of buildings, including a 2D layout and CAD models (Figure 3). Participants were asked at random to use the models to design a building for different purposes: an architectural office, a dream house, and an art gallery. These tasks were appropriate as existing building models were used, and the task could be completed within 75 minutes. The challenge was to use the 2D layout and the 3D model to design for different purposes. In SMM design sessions, the participants worked on the 2D layout by sketching, followed by CAD modelling; while, in AMM sessions, the participants were allowed more freedom and could use both sketching and CAD modelling at will.

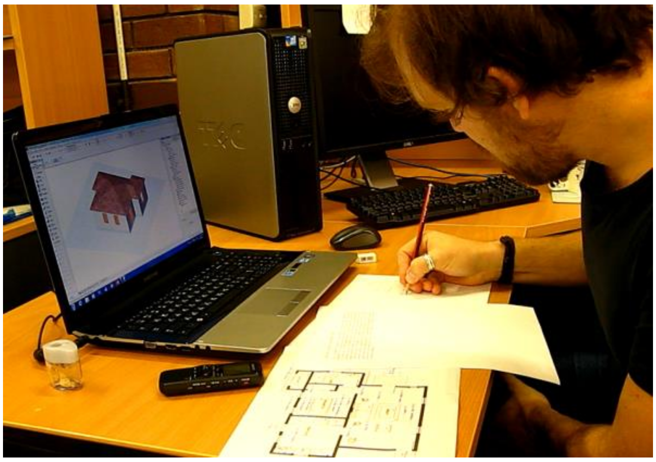
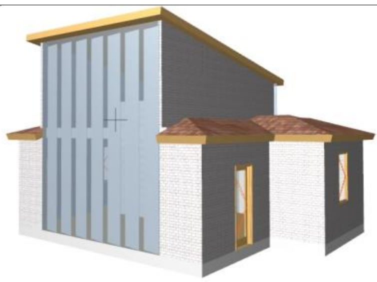


Figure 3. Participant worked on an existing house CAD model and 2D layout

PRELIMINARY RESULTS AND ANALYSES

The results of the study were drawn from SMM and AMM experiments (Table 2).

Table 2: Overview of SMM and AMM experimental designs

	Participant-A	**Participant-B**
Design briefs for SMM	Art Gallery Design	Architectural Office Design
Total time	65 minutes	70 minutes
Task completion	Yes	Yes
Their outcomes		
Design briefs for AMM	Architectural Office Design	Dream House Design
Total time	58 minutes	62 minutes
Task completion	Yes	Yes

Their outcomes		

Appropriate design protocols for the study included recording all forms of the designers' overt behaviours, such as verbalisation, sketching, CAD modelling, and switching between media. This resulted in missing switching protocols. Table 3 shows examples of the FBS codes of the AMM protocol without switching interviews.

Table 3: Example codes of the AMM protocol without interviews

Numbers	Context	Code	Notes
25	think about circulation of the door	Fs	N/A
26	draw an arrow	Ds	N/A
27	check the CAD model with views of different angles	Bsc	N/A

Table 4 shows examples of design switches including 'eye' and 'eye with hand' from sketching to CAD modelling, and from CAD modelling to sketching. Participants were interviewed after completing AMM sessions and asked to identify and explain their reasons for switching media by looking at their videos of AMM design processes.

Table 4: Examples of the participants' switches

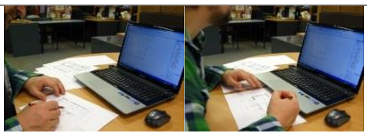
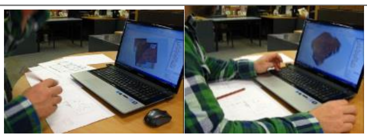
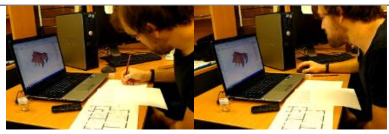
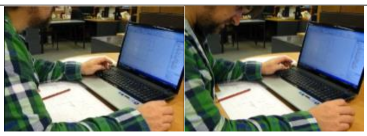
Design switches	Types	Participant-A	Participant-B
Sketching→ CAD modelling (S→C)	Eye		
	Eye and hand		
CAD modelling →Sketching (C→S)	Eye		
	Eye and hand		

Table 5 shows the inclusion of interview excerpts as new segmentations. This enabled the FBS codes to be contextualised. For example, the code (no.28) of segment 'check the CAD model with views of different angles' was revised from Bsc to Dc to acknowledge the impact of the switch noted in the interview.

Table 5: Example codes of the AMM protocol with switch interviews

Numbers	Context	Code	Notes
25	think about circulation of the door	Fs	N/A
26	draw an arrow	Ds	N/A
27 Insert the switch-1	Once the sketching design process was completed through sketching I moved it to the CAD model to realise the design completed through the sketching process. Using the sketched design as a reference point to help the design to be completed in the CAD environment.	Dc	(S→C) insert switch interviews
28	check the CAD model with views of different angles	Dc	Bsc→ Dc

Comparison FBS design issue distributions between SMM and AMM sessions

A high level of agreement was achieved between arbitrated protocols. Two rounds of coding were conducted during a two week period (Gero and McNeill, 1998). The coding consistency shown in Table 6 demonstrates that the coding was reliable.

Table 6: Summary of segmentation and coding results

Participants	Sessions	Coding 1 vs. Arbitrated (%)	Coding 1 vs. Arbitrated (%)
Participant - A	SMM	76.5	84.8
	AMM	74.1	86.3
Participant - B	SMM	77.2	82.7
	AMM	72.8	85.4

Since the design sessions and participants varied, the study normalised the frequency distribution of design issues by converting to occurrence percentages (Figure 4). Participant-A and participant-B produced quantitatively similar distributions for design issues in SMM and AMM. The six design issues were divided into three groups in the following order: structure (S) and documentation (D) > behaviour derived from structure (Bs), expected behaviour (Be) and function (F) > requirement (R). In AMM design sessions, documentation (D) of participant-A was significantly higher than that of participant-B (34.1% > 12.5%). In contrast, requirement (R) of participant-B was significantly higher than that of participant-A (11.8% > 3.2%). These changes demonstrate that participants' switches may have impacted on their design processes in AMM sessions.

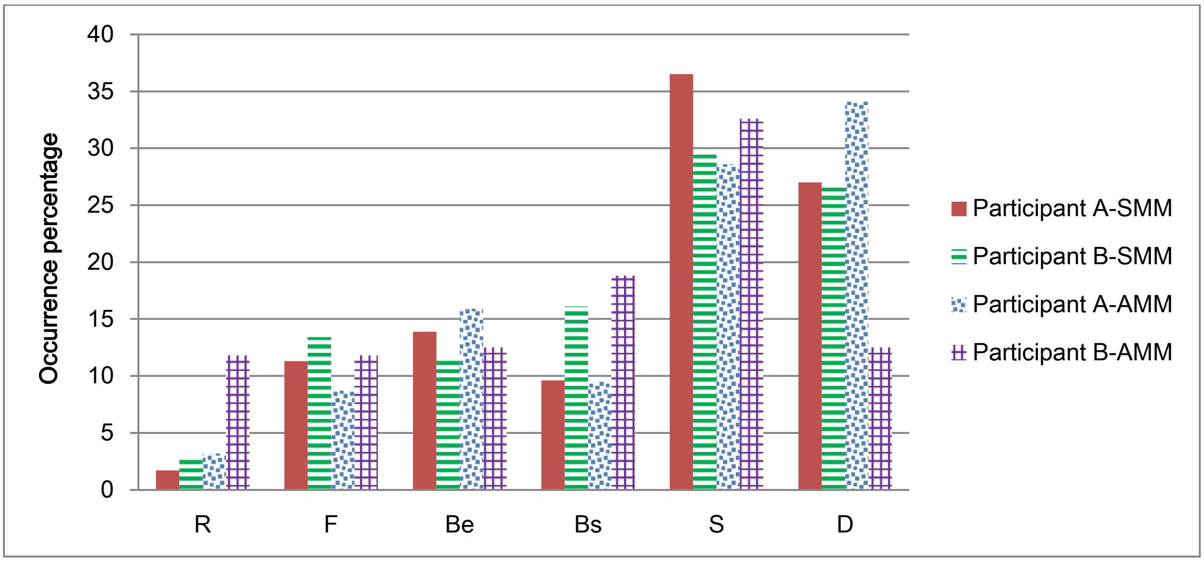


Figure 4. Design issue distributions of participant A and B in SMM and AMM sessions

Figure 5 presents the aforementioned two design issue distributions in sketching and CAD modelling in SMM and AMM design sessions. A comparison of the two participants' results shows that the total distribution of documentation (D) in SMM is similar as is the percentage for using sketching and CAD modelling. On the other hand, participant-A produced a higher percentage on documentation (D), and a higher percentage on sketching and CAD modelling distributions than participant-B. There are a number of reasons why participant-A's switches changed the design issues from structure (S) to documentation (D) when switching from sketching to CAD modelling: 'Transferring the sketch plan to the CAD environment' and 'Then moved it onto CAD', as defined for the first type of design switch (S→C) in the context of the paper. Referring to Table 1, the segment for making a new component in CAD should be coded as structure (Sc). However, for the reasons mentioned above, for design switch (S→C), the same segment will change to documentation (Dc) because the participant transferred sketches into CAD.

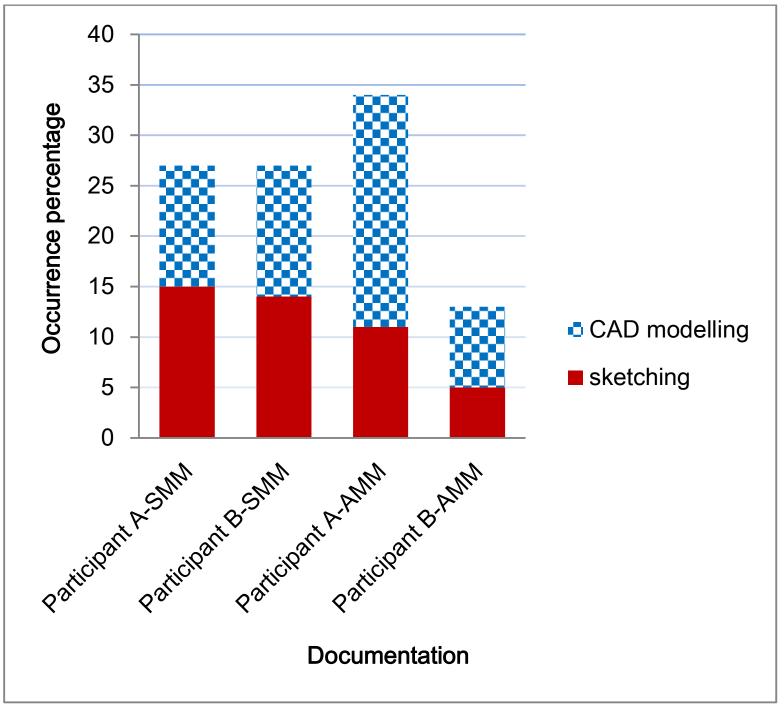


Figure 5. Documentation distributions of participant A and B in sketching and CAD modelling

Figure 6 shows how participant-A facilitated the design process when switching between media. First of all, the participant found it challenging to locate an appropriate place for a stair using CAD. The participant therefore switched to sketching (C→S) to refine and evaluate different locations. Once satisfied, the participant transferred the sketches in CAD (S→C).

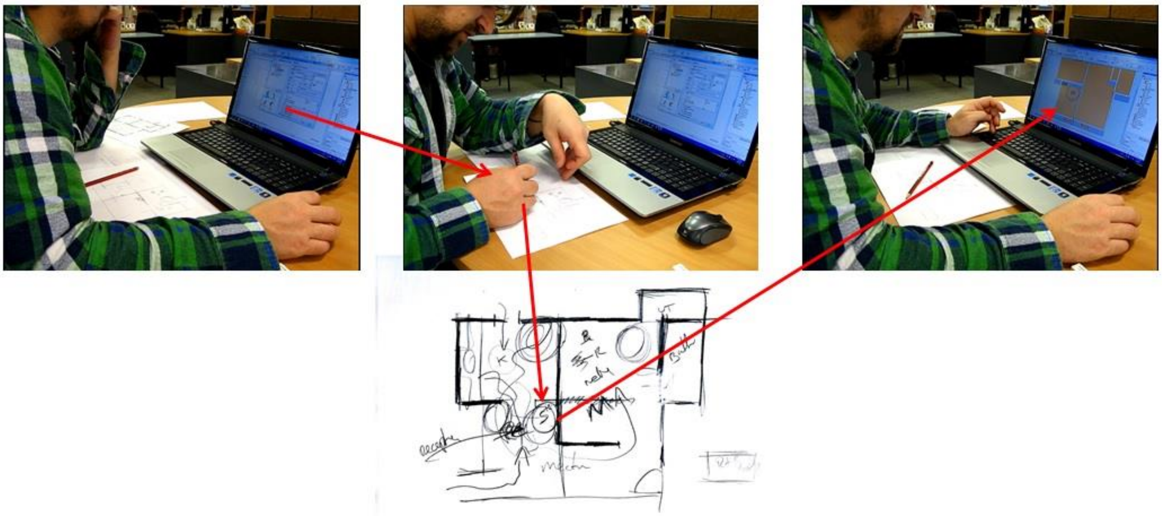


Figure 6. Examples of participant-A design switches

Figure 7 shows that participant-B produced the highest percentage for requirements (R) because of regularly switching between media and the design brief. The reasons given included:

'I moved from sketching to the CAD environment because I wanted to start designing in a virtual setting to understand the spatial and scale requirements of the brief. I noted that as

the 3D model is readily available, I can begin to make immediate changes to form the new design proposal';
'I noted that I was cross-checking the requirements of the brief so I can keep on task with my current design intentions'; and
'In the final stages of completion, I noted that I was switching back and forth so I can check that I have satisfied the requirements of the set brief',

The participant was switching back and forth between sketching/CAD modeling and design brief, as defined for the second type of design switch (S/C⇆R) in the context of the paper. In addition, this type of design switch refers to Cross and Drost (1999) and Suwa et al. (2000)'s protocol studies such as 'situative invention (S-invention)' and 'co-evolution'. Cross and Dorst (1999) posited the modelling of design creativity as a co-evolution for both problem and solution spaces. According to Suwa et al. (2000), S-invention refers to designers' activities that extend beyond the initial definitions of the problem-space, helping designers to form new goals to address significant parts of design problems.

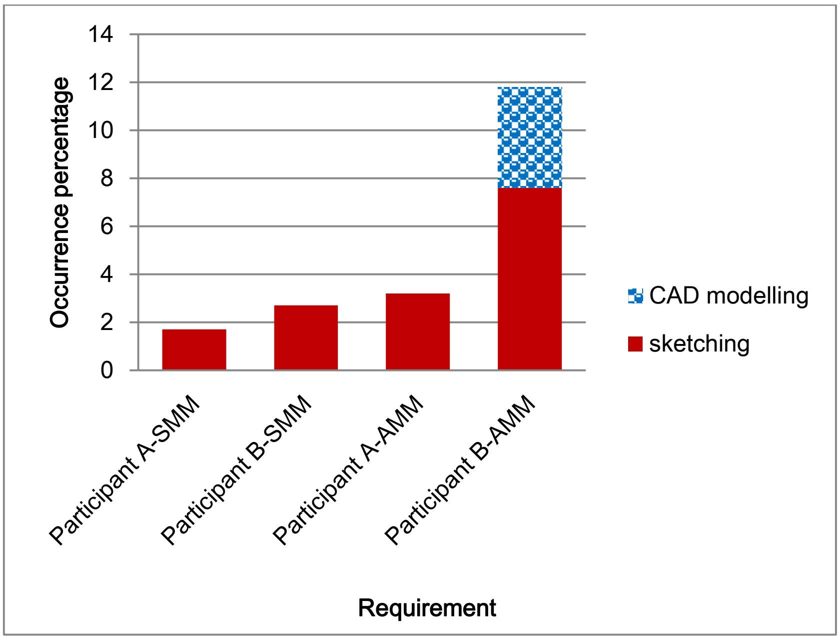


Figure 7: Requirement distributions of participant A and B in sketching and CAD modelling

DISCUSSION

In general, sketching allows design solutions to be stored and subsequently evaluated. This helps designers recognise different design possibilities (Akin, 1978). By contrast, it is not possible to store alternatives on a screen when CAD modelling is used. Designers need to undo and redo their CAD models when changes are required. The two design processes, SMM and AMM, may lead to changes in the roles of design mediums. Using AMM (i.e. being able to switch between media) allows designers to engage effectively in their design processes and find appropriate solutions to problems. For instance, Figure 6 shows that participant-A was fully engaged in design processes using AMM. However, participant-A mentioned 'I get stuck' several times during CAD designing section when using the SMM approach.

Participants' comments

Participants provided comments on completion of both experiments. Their feedback about SMM was that they would not be capable of designing using CAD if they were not allowed to switch. The common view was that if they were allowed to switch between media they would have evaluated their ideas quickly at both abstract and concrete levels. On the other hand, completing activities in AMM design environments were likened to tracing ideas between sketching and CAD modelling. Their view was that by switching between media they were able to complete their design tasks smoothly. This relates to the concept of the 'right-tool-right-time', (Do, 2005: 396) and that such usage would actually engage participants thinking along creative pathways.

All participants believed strongly that switches were essential. They summarised the contribution of being able to switch as follows:

1. Switching is essential: 'I think the combination of sketching in tandem with CAD tools offers the designer a great freedom of design expression, having the ability to cognitively work between two mediums. This process of switching mediums, in my opinion, is the ideal design format for conceptualisation'.

2. Switching is a natural design workflow: 'Many designers use sketching, mostly as visual notes, to rapidly memorise a design idea. CAD is useful to record the ideas and extend the development of the visual notes taken whilst thinking about the design and reflecting upon the design requirements. Using CAD as a permanent record of design ideas that are ever changing on paper helped me stabilise the design workflow. For me personally it was easy and natural to switch between mediums as it forms a very natural and complimentary workflow'.

3. Switching has potential for creative engagement with interactive mediums: 'I found it quite natural to work in the AMM session, I felt I could achieve better results by sketching first and then going back to alter in tandem with the CAD tools provided'.

Categorisation of three types of switching between media

While Table 4 and Figure 6 demonstrated several design switches between media, the results of the study can be categorised into three types of switches:

1. The first type of design switch, from sketching to CAD modelling (S→C), changes a design issue of the FBS coding scheme from structure (S) to documentation (D): 'I was trying the hand-sketched design in the CAD environment so as to better understand its function in terms of scale, section and elevation' and 'moved it onto CAD'.

2. The second type of design switch, back and forth between sketching/CAD modeling and design brief (S/C⇆R) within seconds, evaluates the similarities and differences between sketches/CAD models and design briefs which was coded as requirements (R): 'I was switching back and forth so I can check that I have satisfied the requirements of the set brief'.

3. In the third type of design switch, from CAD modelling to sketching (C→S), the participants preferred using sketching to refine their ideas than using CAD modelling: 'I was sketching another spatial variation of the floor plan to better understand the spatial qualities at a conceptual level'.

Implications for design research and practice

This study compared cognitive behaviour in SMM and AMM design environments. It provides empirical evidence to better understand two approaches of integrating sketching and CAD modelling. The FBS coding scheme was developed to fit mixed media design environment studies and allow researchers to compare overall design processes as well as changes of cognitive behaviour within indiviual design mediums. The development of coding schemes and the techniques of combining these with switching protocols are transferable for future investigations about the integration of design mediums.

The empirical results suggest that switching is essential. It is a natural design process and has the potential to generate creative engagement with interactive media to help participants achieve better design outcomes. The three types of switches, S→C, S/C⇆R and C→S, serve different roles for participants to facilitate their designs. It is likely that preventing participants from switching for more than one hour would have resulted in an excessive cognitive load which would have resulted in frustration and inertia. The switches between media require much less cognitive design process load.

CONCLUSION

The main question addressed in this study was whether participants' switches between sketching and CAD modelling influence design processes. First, the results show that the designers switched many times between sketching and CAD modelling during AMM design processes. Second, two design issues (S and Bs) of the FBS coding scheme were changed to design issue (D) after switching from sketching to CAD modelling (S→C). A possible mechanism by which designers' switches influence design processes is Do's concept of 'right-tool–right-time', (Do, 2005: 396). This also supports Coyne et al.'s (2002) research with respect to the integration of conventional and digital methods for sketching: each is valued rather than one replacing the other. Some studies of cognitive behaviour (Chen, 2007; Ibrahim and Rahimian, 2011) have found mixed media to be the most effective external representation aids because they generate higher quality solutions than when CAD modelling is used in isolation. However, most participants in these studies were asked to initially use sketching before shifting to CAD modelling. Interestingly, in the study reported here, it was observed that both participants spent more time on CAD modelling than sketching. One advantage of this study is the AMM experimental set-up, which is close to the circumstances of natural design. In conclusion, this study has demonstrated that both participants' switches were effective in influencing design processes because the switches integrated both sketching and CAD modelling as one design medium.

The current study is based on the two participants' protocols in the SMM and AMM sessions combined with interviews about switching. These activities produced a large amount data and provided opportunities to test various experimental settings. However, the sample size of this study is more modest than other protocol design studies. To better understand mixed media studies, further investigations with a larger sample size will be conducted.

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EXPERIENTIAL LEARNING STYLES IN THE AGE OF A VIRTUAL SURROGATE

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Abstract
There is a long-held sense in general that the increasing use of computers and digital technology changes how a user experiences and learns about the world, not always for the better. This paper reports on a longitudinal study of 245 architecture and construction students over a two year period which examines the impact that virtual reality technologies have on the learning style preferences of students. A series of controlled experiments tests for the impact that increasing exposure to a proprietary virtual reality system has on the mode of learning and learning style preferences of individuals and particular cohorts. The results confirm that when virtual reality applications are used in teaching and learning, the learning behaviours will favour a more concrete experiential mode of learning and a preference for the Accommodator learning style. However, the results also demonstrate, consistently and for the first time, individual students do not privilege any particular mode of learning or learning style preference to any significant extent but rather engage in all modes and represent all learning styles. Novel visualisation techniques are introduced to examine and discuss this contrast.

Keywords: *Virtual reality, experiential learning model, learning style inventory*

INTRODUCTION

The widespread use of computers and digital technology is not only changing our lives, but has already become ingrained. The physical world is blending with virtual content and people are living in an extended space enhanced through digital technology. With the growing impact of digital content the experience of learning and teaching in higher education is being changed significantly. Very soon the majority of students entering higher education will have been born during or after 1998, the year Google was launched. Higher education faces a generation of students who have only ever known life with Google and the growing plethora of mobile digital devices. It follows that the ways in which this generation interacts with the world and the things they expect from their learning experiences are likely to be very different from how previous generations have engaged.

There is a long-held sense in general that the increasing use of computers and digital technology changes how a user experiences and learns about the world (Halverson and Shapiro, 2012; White et al., 2014), not always for the better (Margaryan et al., 2011). In architecture education in particular, there is anecdotal concern that the educational experience could become impoverished if creative expression is in some way confined to the use of digital technology. The more general consensus seems to be that digital technology can facilitate learning by at least providing further expressive options. As highlighted by Starkey (2011), the current challenge for teachers is to convert established learning theories into new practices that most effectively leverage and engage the upcoming, digitally literate generation.

Over the past decade and more computer software, most especially Computer-Aided-Design (CAD) software, has been adopted increasingly for architecture and construction teaching and learning. Some argue that the role of digital technology in teaching and learning is now critical (Ham, 2013). Ham and Schnabel (2014) claim that effective learning experiences rely on the successful acquisition of skills using a combination of digital and physical media. They challenge architecture educators to reposition the role of digital technology in architectural design courses by considering the actual working, learning and engagement styles of students. This paper reports on a study of the impact emerging digital technology is having on the learning styles of architecture and construction students and what that might mean for how those subjects are taught. The study is motivated by developments in virtual reality (VR) technologies that support a more immersive and experiential approach to learning. This locates the study at the developing confluence of VR technology, itself still under development, and the literature specific to experiential learning and learning styles.

BACKGROUND ISSUES

VR Technology in Learning

In architecture education the three most fundamental components are knowledge, skill and design, with the teaching of design often regarded as being the most challenging aspect (Chakradeo, 2010). Nabih (2010) argues that there are gaps between the theory and practice of architectural design that require addressing through a problem-based approach to learning rather than a traditional lecture-based format. Chee (2007) highlights the importance of directly engaging students with the experience of architecture. However, the resource and practical difficulties of embedding large student cohorts in actual architectural practice and providing direct experience of key architectural designs are prohibitive. Digital technology is proffered increasingly as a potential alternative to direct experience. VR technology is of particular interest in this regard (Dalgarno et al., 2011).

VR technologies use high performance graphics engines to render moving photo-realistic scenes in real-time and in three-dimensional (3D) perspective combined with associated surround-sound audio and tactile feedback to a user. The user interacts with the virtual environment through a variety of input and output devices. Such virtual environments are considered to be of potential benefit in framing the development of knowledge in architecture education (Yan et al., 2011). However, there is ongoing debate on the most effective role for computers and VR technology as tools in learning and teaching (Margaryan et al., 2011; Starkey, 2011). It is reasonable to assume that with increased realism student engagement with a virtual environment will be improved and learning outcomes will improve as a consequence. However, insufficient evidence is available in the existing literature to confirm those links.

Studies have been conducted on the use of VR technology in architectural design and education. Rahimian et al. (2011) focussed on how a designer interacts with the external design representation to conclude that the use of VR can improve both the cognitive and collaborative activities of designers. Game-like VR interfaces have also been applied within the context of architecture and design education to promote more creative design decision-making (Sampaio et al., 2010; Rahimian et al., 2014). However, according to Abrishami et al. (2015), previous studies of VR applied to architecture and construction have tended to focus on the advanced visualisation potential rather than the broader-based, more blended experiences possible with advanced VR. Certainly the capacity for VR technology to simulate a broader range of performance criteria than just the aesthetic considerations is now being addressed (Leinonen et al., 2003; Goulding et al., 2014). However, the impact on student learning experiences that advanced visualisation and the broader simulation potential of VR could have is not yet clear. Emerging VR technology, for the first time, offers an authentic hyper-immersive learning experience at an affordable price and in a technically feasible format for large cohort teaching. With this watershed it is now timely to investigate how VR might impact the student learning experience in architecture and construction education more directly.

Any application of VR to education must consider the distinction made by Bomsdorf (2005) between a digital learning space and a digital learning context. A digital learning space comprises the particular digital exercises undertaken by a learner, where the context refers to a broader set of circumstances through which sense-making and fundamental understanding are formed. It is a condition of the immersive nature of VR technology that learning space and learning context often become conflated, as the learner is using the virtual environment to achieve particular outcomes and at the same time using the experience to form and test broader experimental hypotheses. For example, the specific properties of a VR simulation also contain the broader situation that renders each learning activity meaningful (Thevenin and Coutaz, 1999). These properties are peripheral to the particular learning exercise, but directly impact the behaviour and learning process of a learner (Cui and Bull, 2005). The blurring of boundaries between learning space and context challenge many established theories of learning. The most significant impact of VR on learning may not be about the technology itself at all, but rather the radically different potential configurations of learning space and context that VR tends to promote (Schwanen et al., 2008)

In the light of the various challenges to established learning theory being wrought by emerging digital technology, traditional theories are being adapted. For example, the active construction of knowledge using 3D environments encourages more exploratory modes of action (de Freitas & Neumann, 2009) and collaboration now includes working collectively at a distance (Bower et al., 2014). However, adaptation may not be sufficient in the case of experiential learning theory, where the transactions between learner and environment are fundamentally changed in a VR context.

Experiential Learning Theory

Vygotsky (1978) claims that learning from experience is the central process of human development. One of the most influential educational theorists of the 20th century, Dewey (1958), provided guiding principles for experiential learning theories. Lewin (1951), although focusing on organizational learning, later established that “learning is best facilitated in an environment where there is dialectic tension and conflict between immediate, concrete experience and analytic detachment”. The development of Lewin’s theory was continued after his death by others such as Festinger (1962), and it has had a profound influence on the practice of adult education, training and organizational development. Another influential theorist was Piaget (1950), whose work focuses on child development and how intelligence is shaped by experience. According to Piaget (1950) intelligence is not an innate internal characteristic of the individual, but rather “a product of the interaction between the person and their environment”.

Kolb and Goldman (1976) established, and Kolb (1984) further developed, an experiential learning model (ELM) based on six propositions drawn from the literature:

- Learning should be conceived of as a process, not in terms of discrete outcomes. Feedback on the effectiveness of an individual’s learning efforts is the best way to improve learning.
- All learning is relearning. Drawing out the beliefs and ideas that a learner already has about a topic enables them to be examined and tested. More refined ideas and knowledge need to be integrated with existing constructs.
- Learning requires the resolution of conflicts between dialectically opposed modes of understanding of the world. The learning process is one in which a learner will “move back and forth between opposing modes of reflection and action and feeling and thinking” (Kolb, 1984).
- Learning is a “holistic process of adaptation to the world, since it involves the integrated functioning of the total person” (Kolb & Kolb, 2005), which includes thinking, feeling, perceiving, and behaving.

- Learning is a result of synergetic transactions between the learner and the environment, a process of assimilating new experiences into existing concepts and projecting existing concepts onto new experiences.
- Learning is a social process of creating individual knowledge created and recreated through the personal knowledge and interactions of individuals.

Having conceptualised experiential learning Kolb and Goldman (1976) went on to develop the learning style inventory (LSI) to measure and identify different learning style preferences. Many researchers have now used this instrument in studies and there have been various critiques and suggestions for improvement of both ELM theory and the LSI. In response, several major updates of LSI have been developed, in 1984, 1991, 1999 and 2005.

Kolb (1984) maintains that learning is one continuous process of knowledge creation and not a series of contained learning outcomes. According to ELM, learning involves four related intellectual processes through which the learner interacts with a learning environment. In one dimension is the process of grasping experience and understanding events based on that experience, where apprehension is the counterpoint to comprehension. In the other dimension is the process of transforming experience into knowledge and understanding, where intention is the counterpoint to extension. Based on these intellectual processes, ELM is defined as a four-stage cycle consisting of four modes – concrete experience, reflective observation, abstract conceptualisation, and active experimentation (See Figure 1). From this theoretical framework Kolb introduced the concept of learning styles (Kolb and Goldman, 1976; Kolb, 1981; Kolb, 1984). Learning styles assess the orientation of an individual towards each of the four learning modes. Kolb (1984) points out that each individual learns differently because of the diversity in cognitive functioning, the scope of the content being focused on and the different sociocultural experiences. Such differences in learning styles ultimately result in different learning experiences.

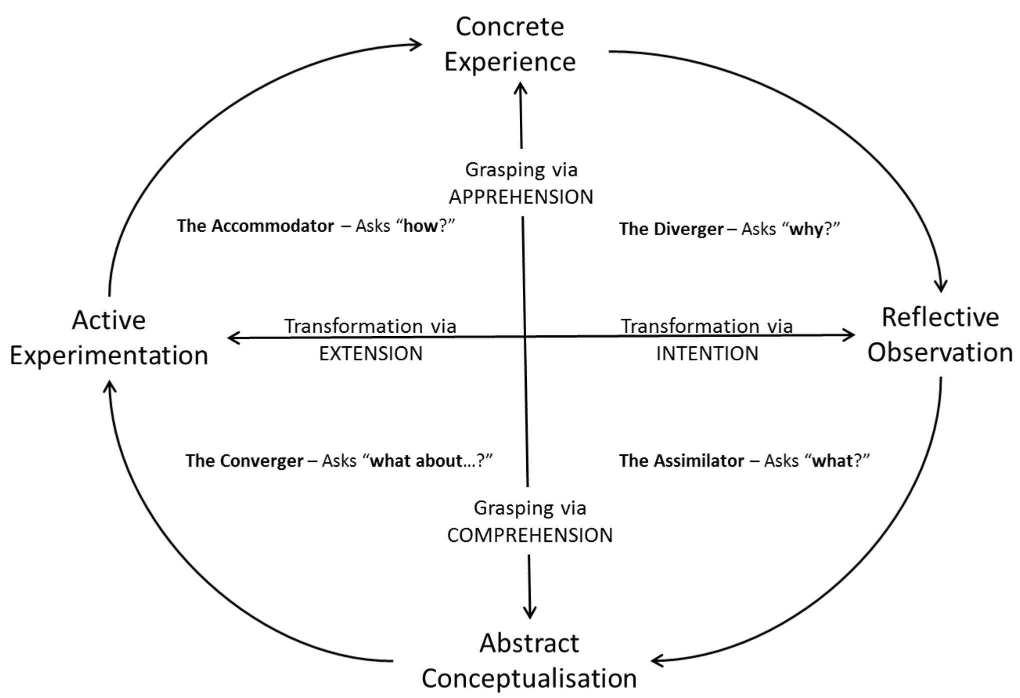

Figure 1: Adapted to summarise a number of separate illustrations relating to Kolb's Experiential Learning Model (Kolb, 1984)

Experiential learning is then characterised in terms of a four-stage cycle that covers the four learning modes that come from the four intellectual processes described. Figure 1 presents the ELM in terms of the two key dimensions of grasping and transforming. Concrete experience (CE) is a mode in which people grasp experience through apprehension and rely on their feelings to initialise or motivate learning. Abstract conceptualisation (AC) is a mode in which people grasp experience through comprehension and thinking is the main strategy for learning. Reflective observation (RO) is a mode in which people transform experience through intention and during which learners learn by watching others. Active experimentation (AE) is a mode in which people transform experience through extension and during which people learn by doing. Learners go through all four of the learning stages, but each individual learner tends to emphasise one or more of the four modes of the learning process at any given point in their learning activities. This emphasis is claimed to determine the learning style of the individual (Kolb, 1984).

ELM is not the only conceptualisation of learning style possible. There have been many diverse learning-style definitions and models proposed (Curry, 1990). Often the alternative models have strong parallels with ELM, in that they also reference four continuous dimensions but name and describe them differently (see for example, Honey and Mumford, 1982). Other alternatives seek to expand the number of dimensions being considered. For example, the early work of Dunn and Dunn (1992) proposed a far broader-based model that included environmental, emotional, sociological, physiological and psychological elements. Other alternatives again, tend to focus on more specific learning contexts and fields of study, such as early learning development ( ) or engineering (Felder and Silverman, 1988). Several of these alternatives have been widely adopted and tested for reliability and validity (see for example, Felder and Spurlin, 2005), but in general no particular model is without criticism and none has been more widely adopted or as influential as ELM. Furthermore, the alternative models often require extensive questionnaire instruments in order to assess the learning style preferences of individuals (see for example, Dunn et al., 1995).

In contrast to many other models, the ELM is associated with a relatively modest multi-item questionnaire (the LSI) developed to identify and categorise the learning style preferences of individuals. The LSI categories draw from each quadrant of the ELM and classify learning styles in terms of:

- Divergers, who grasp experience through apprehension and transform it via intention – divergers prefer learning by watching and feeling, and tend to ask “why” questions.
- Assimilators, who grasp experience through comprehension and transform it via intention – assimilators prefer learning by watching and thinking, and tend to ask “what” questions.
- Convergers, who grasp experience through comprehension and transform it via extension – convergers prefer learning by doing and thinking, and tend to ask “what about” questions.
- Accommodators, who grasp experience through apprehension and transform it via extension – accommodators prefer learning by doing and feeling, and tend to ask “how” questions.

Learning Styles

The learning style inventory (LSI) was developed to measure and identify the relative preferences an individual or group of learners have along each dimension of the experiential learning model. The LSI Version 1 (Kolb and Goldman, 1976) contained just nine items/statements, each with four alternative endings that represented each of the four learning styles. In LSI Version 2 (Kolb, 1984), a further three items were included bringing the total number to twelve. Each item in the LSI takes the form of a descriptive sentence with a choice of four alternative endings. Each ending to each sentence represents one and only one of the four learning modes. For example, the sentence beginning “When I learn…” might have the following choice of endings:

“… I like to deal with my feelings.”, CE;

"… I like to watch and listen.", RO;
"… I like to think about ideas.", AC;
"… I like to be doing things.", AE.

Respondents are required to rank each of the endings for every sentence based on how well each one describes how they prefer to learn. The ranking starts with a "4" for the ending that best accords with their learning preference, down to a "1" for the ending that accords least. Each alternative ending must be ranked and all must be ranked differently.

In both Versions 1 and 2 the order in which each ending related to each individual learning style remained constant. In other words, the first ending always aligned with the same learning style and so on for the other three endings. This characteristic was rightly criticised for introducing bias towards those learning styles aligned with the initial response (Ruble and Stout, 1990). LSI Version 3 (Kolb and Kolb, 2005) adjusted the ordering of the endings so that the learning style alignment was more random.

To determine the learning style preference, a total score is calculated for all designated CE, RO, AC, and AE endings. Thus, where a given mode is ranked highest for every one of the twelve sentences the maximum score is $12 \times 4 = 48$. As all endings must be ranked the minimum score for any given mode is $12 \times 1 = 12$. The overall score should always be $12 \times (4 + 3 + 2 + 1) = 120$. Once the totals for all four modes are calculated a location along each of the two dimensions is determined by calculating a balance point between each score on that dimension. For example, the result of [AC – CE] provides a position on the grasping (comprehension/apprehension) dimension, which is then referred as the AC-CE score. The result of (AE – RO) provides a position on the transformation (extension/intention) dimension. A measure of the particular learning style is then provided in two ways: either as a quadrilateral plotted by joining the coordinates of each individual mode total score; or as an individual point to represent the average location (centre) of the quadrilateral thus formed.

Research Question

There is a long-held sense in general, and in architecture education in particular, that the use of computers conditions (biases) the ways in which an individual learns about the world and that this could be to the detriment of the educational experience (Bandyopadhyay et al., 2010). When virtual reality applications are used in teaching and learning the learning behaviours are expected to favour a more concrete experiential mode of learning and a preference for the Accommodator learning style. Is such an impact observable? If it is not the concrete experiential learning style, then is some other learning style being favoured? Or is a more fundamental change in learning styles evident? There is a definite knowledge gap in this regard.

The research problem is how to investigate emerging virtual reality technologies and how they impact the way people experience the world in a learning context. It is in the nature of emerging technologies that they tend not to be well-embedded already in teaching programs. It is in the nature of human experience that objective measures are difficult to determine. This study takes a broad perspective on VR technology with a focus on a particular implementation (The Situation Engine) specifically developed to support teaching and learning in architecture and construction, and already in use within the teaching programs of several Universities in Australia. The LSI represents a very popular measurement instrument for determining learning style preferences. It has been extensively applied, discussed and developed. Nevertheless, the application of LSI needs to be part of the research consideration in and of itself. It is necessary for the research methodology to consider the research instrument (LSI) just as much as the fundamental research question. Notwithstanding the broader research consideration, the key research question is identified as:

To what extent is VR conditioning the way people engage in learning and what are the implications for the education process?

RESEARCH METHODOLOGY

To address the research question, a two-phase experiment was designed. In both phases of the experiment students were contacted and invited to participate using a class announcement made by the class lecturer. Participation was entirely voluntary on the part of the students and there was no grading associated with the exercise. During the first phase of the experiment the LSI survey was deployed three times: at the beginning; the mid-point; and at the end of the semester, with five weeks interval between each deployment. In the second phase, high-performance computers were provided to run a VR exercise using a proprietary system, The Situation Engine (www.situationengine.com). The Situation Engine is an application that provides for specific and managed practical building and construction experience to be made available to students using advanced video game technologies (Newton, 2012).

The LSI was used as a measure of the learning style preferences of participants. Instructions on how to use the LSI was provided on the first page of the survey booklet. These stressed that "no two endings in a set can be given the same ranking", and that a score of "4" is the most descriptive of the participant while a score of "1" is the least descriptive of the participant. The instructions also emphasised that there are no right or wrong answers and that the participants should use their first impressions to answer each question as honestly as possible. Completing the full LSI survey usually took no more than five minutes for each participant. Following the suggestion of Ruble and Stout (1990) to avoid set bias, a "scrambled" version of LSI was developed in which the order of the endings were randomly arranged in terms of the learning style each represented. To further avoid the potential bias that one particular randomised version might bring to the results, four different sets of "scrambled" LSI were deployed in each experiment session.

The experiment was undertaken in the Faculty of Built Environment, University of New South Wales (UNSW). 245 undergraduate students at this university were chosen as the sample because they represented a contained and recognised educational cohort in terms of age and other demographics. Three stages of VR technology use were identified in Phase One during the teaching of ARCH1101: Architectural Design Studio – a first semester, first year architecture core course. The first stage was at the beginning of the teaching semester, when participants had minimal (if any) exposure to VR learning contexts. At the beginning of the semester most of the students were just commencing their studies and still transitioning from their experience of high-school study to university life. At this stage it was unlikely that the students would have had previous exposure to teaching and learning using VR, although they may have been exposed to some digital learning technologies such as online search engines and rudimentary online learning management systems.

The second stage was timed at the mid-point of the teaching session for ARCH1101: Architectural Design Studio, when participants had been introduced to VR technology and learning contexts as part of their studies but were yet to use the technology to accomplish a major assignment. During ARCH1101: Architectural Design Studio, students are progressively exposed to a number of 3D modelling systems such as Google SketchUp and Autodesk 3DS Max. They are also introduced to VR by having to complete assessment tasks using real-time interactive game engines to construct virtual worlds. Students have rarely had previous experience in the high-end 3D modelling systems or VR game engines included in this program of study. By the mid-point of the semester students had a reasonable understanding of VR technologies in theory and some basic skills in using VR to learn architectural design. However, the skill-base was still rudimentary and few students were capable of completing the major assignment task for the subject at this stage.

The third stage was towards the end of the teaching program, when participants had more advanced skills in VR and have substantially completed a significant independent assessment task using the VR technology.

This component of the research was designed to investigate whether student learning style preferences change over the course of study with increasing exposure to VR technology. The same student cohort was surveyed using the same LSI three times during their first semester, 2012. The LSI survey was deployed mainly in a pen-and-paper based format when practical, and the feedback was collected on the same day as participants undertook the experiment in order to ensure high response rates and the currency of responses. Any changes in individual student learning style preferences over the course of the semester as participants progressively learned more about the concepts and skills of VR would be apparent.

To further test whether the VR technology has immediate influence on learning style preferences, in addition to the longitudinal study described above, a lab-based study was also designed as Phase Two of the experiment. In Phase Two, each participant was assigned a small learning task and given a short period of time to accomplish the task in a virtual learning environment, as shown in Figure 2. The aim of the lab-based experiment was to test the immediate influence of VR technology on learning style preferences. In this phase the sample was extended to include participants enrolled in a broader range and variety of subjects within the Faculty of Built Environment, UNSW. Participants in Phase Two were recruited from: ARCH1101: Architectural Design Studio, BLDG1211: Domestic Construction, and ARCH1392: Collaborative Design Studio. These particular courses were selected because the use of The Situation Engine is highly relevant to these courses and either VR teaching technologies were already being used or there is potential to adopt such technologies in these courses in the future. Including a cohort of students from construction in Phase Two provided some diversity to the sample in terms of study background, work experience and familiarity with VR technologies in teaching and learning. These factors are particularly relevant because the learning tasks for the experiments are set in construction contexts where background and experience could play an important role in the learning style preference.

Figure 2: The virtual environment designed for Phase Two of the experiment.

Data from Phase One and Phase Two of the experiment was collected and analysed. The LSI results collected at each of the three stages in Phase One reflect the extent to which VR technology impacts on learning style preferences over time and with increasing exposure to VR. Data collected from Phase Two of the experiment is specific to the immediate impact of VR technology on learning styles. A significant majority of participants in Phase Two had little or no prior exposure to VR technologies. By comparing the results from Phase Two with those from the mid-point testing of Phase One (the closest equivalent in terms of general student progression), it can be determined whether or not VR technology promotes a particular learning style in a short period. Furthermore, any immediate impact can be compared with the longer-term impact found in Phase One.

RESULTS

The architecture student samples from the first, second and third stages of Phase One are referred to as Group A, Group B and Group C respectively. Also in Phase One (2012), the LSI was administered to a group of construction students enrolled in BLDG1211: Domestic Construction. Those students were taught in a traditional way where VR technology is not used. The sample from the construction cohort is referred to as Group D.

During Phase Two of the experiment (2013), the LSI was administered to a new architecture cohort and a new construction cohort within the same courses as the previous year. However, in 2013 both cohorts experienced learning with VR technology using The Situation Engine. In Phase Two (2013), the LSI was administered to the architecture student sample on two occasions, once in the middle of the teaching semester and once at the end. The architecture student sample recruited in 2013 and surveyed in the middle of semester is referred to as Group E; the construction student sample recruited in 2013 and surveyed in the middle of semester is referred to as Group F; and the architecture student sample recruited in 2013 and surveyed at the end of semester is referred to as Group G.

Given this sampling, if VR is conditioning the way people engage in learning then it should follow that the sequence of Group A, Group B and Group C results will begin to bias a particular mode of learning and learning style preference. It is also the case, because they are drawn from equivalent cohorts at exactly the same stage of study, that the same patterns of learning preference should be presented by Group B and Group E, and by Group C and Group G. The most significant contrast, if exposure to VR in teaching and learning is having any impact, should be between Groups D and F and all other groups.

As described above, to determine the learning style preference a total score is calculated for all designated CE, RO, AC, and AE endings and an average location along each of the two dimensions is determined by calculating a balance point between each score on that dimension. The points are plotted on a two dimensional grid, the LSI grid. The LSI grid mirrors the ELM diagram in Figure 1, and comprises a horizontal AE – RO axis and a vertical AC – CE axis. The position on the AE – RO axis is determined by subtracting the RO score from the AE score. A positive result moves away from the origin along the AE dimension and a negative result moves away from the origin along the RO dimension. The same logic applies to the AC – CE axis location. Each axis is measured from the origin outwards, from 0 to the maximum value. Given the maximum score for any particular learning mode is $12 \times 4 = 48$ and the minimum score is $12 \times 1 = 12$, the most extreme value for either axis will be $48 – 12 = 36$. The individual location used to represent the learning style preference is plotted using the derived AE – RO and AC – CE values.

A further consequence of having two dimensions on a single axis is that the scores on each dimension are not absolute. Kolb (1984) has adjusted the axes accordingly. From a review of all available LSI scores, the average location for the total population is calculated and each dimension is then offset by that amount so that the apparent origin is not necessarily (0, 0). For example, the last review of LSI Version 3 identified 6,977 valid individual LSI scores. The average balance point for each dimension was calculated from those 6,977 surveys as 5.96 on the transformation (AE-RO) dimension (a positive AE-RO value means it is on the AE side), and 6.83 on the grasping (AC-CE) dimension (a positive AC-CE value means it is on the AC side). The convention is then to use this offset datum as the origin of each axis that forms the learning style quadrants. That is, if the balance point of a given learning preference is in the top-left quadrant of the offset point, this identifies an accommodator learner. If the balance point of a given learning preference falls in the bottom-right quadrant of the offset point, this identifies an assimilator learner, and so on.

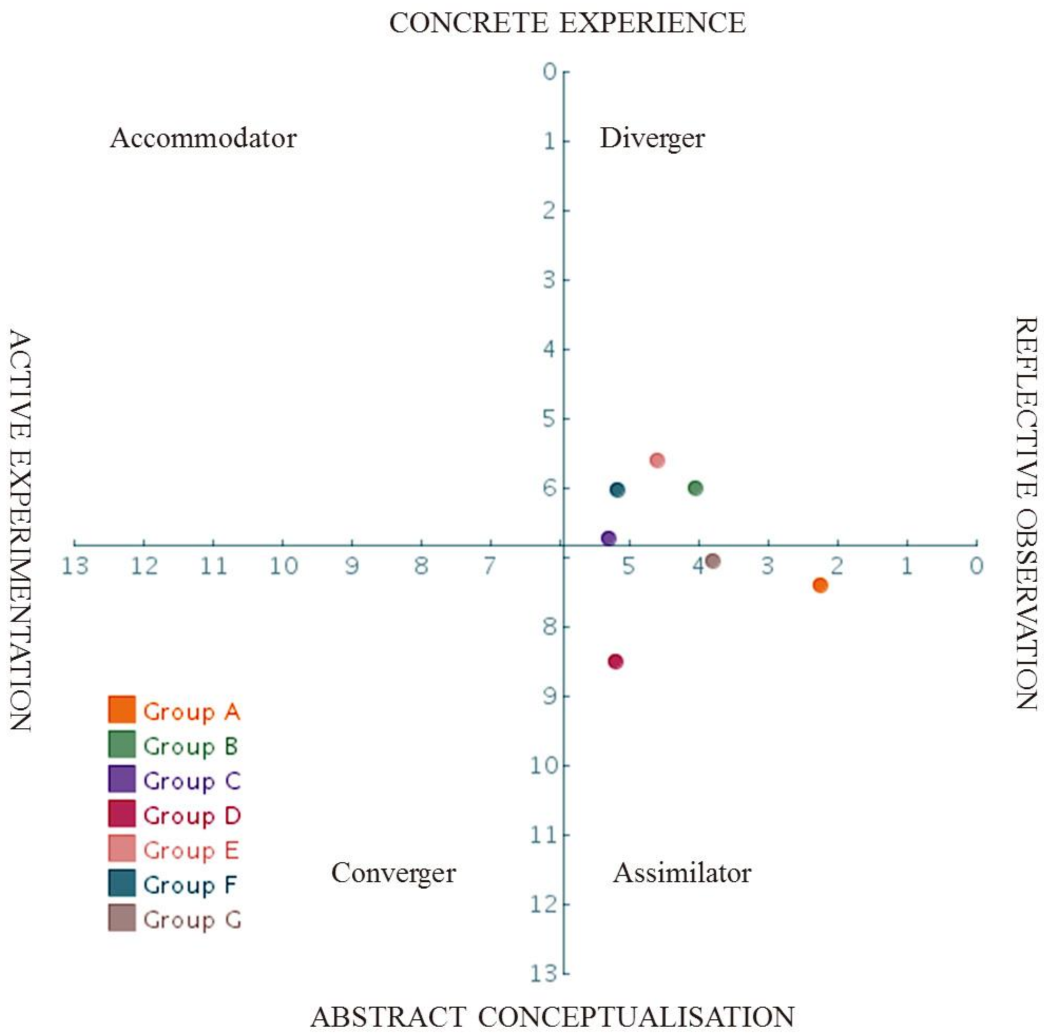

Figure 3: The balance points for each LSI investigation presented on a zoomed-in region with Kolb's offset datum.

Figure 3 illustrates the LSI balance points for each group from the seven investigations. The grid shows a zoomed-in region of the total LSI grid. The origin of the grid is set by Kolb's AE – RO : AC – CE scores and the grid is divided by the blue-green lines. When plotted on this grid the pattern of relationships between the groups can be examined. There does appear to be a sequence of results between Group A, Group B and Group C, as each distinctly moves further along and towards the AE dimension. This would indicate that increasing exposure to VR over time promotes more active experimentation. It is also clear that Group D is an outlier, and that exposure to VR technology in the teaching and learning context appears to move the preferred mode of learning along and towards the CE dimension. Groups D and F both appear towards the AE dimension, suggesting that construction students have a stronger preference for active experimentation. There is some correspondence (closeness) between Groups B and E, and (though less so) between Groups C and G. That would indicate some consistency between equivalent student cohorts from one year to the next. Overall however, the determined learning style preference places Groups A, D and G together as Assimilators and Groups B, C, E and F together as Divergers. There is no apparent underlying explanation for these groupings based on either exposure to VR or to the field of study.

Figure 3 is the classic form of representation for LSI results, and the associations and classifications made about different groups in the previous paragraph are how learning style preferences are typically determined and discussed. However, Figure 4 shows the same results displayed on the full LSI grid. In Figure 4 the distribution of LSI balance points are displayed on an actual LSI grid, with the origin at (0, 0) and the true cross point of the AC – CE and AE – RO axes. In Figure 4, Kolb's offset datum is still represented by the blue-green lines, but from this perspective the results take on a very different complexion. The differences highlighted when zoomed into a specific region pale when placed in the context of a full LSI grid. The immediate impression is how similar and tightly packed the results appear rather than on any differences or spread between them. It is also apparent that from the true origin, all of the groups would have been classified as Convergers.

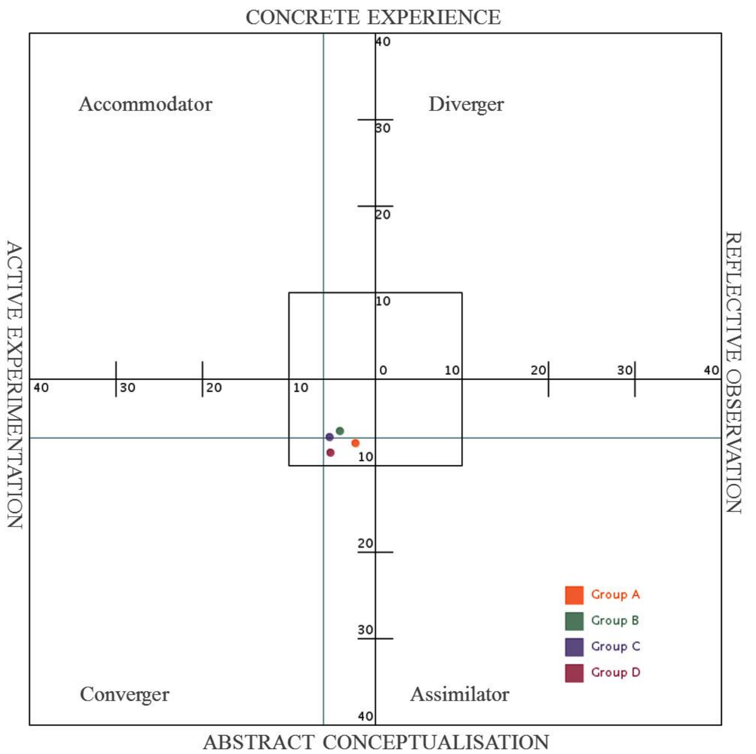

Figure 4: The balance points for each LSI investigation presented on the original/full LSI grid.

This disparity between the zoomed-in representation incorporating Kolb's offset datum and the full LSI grid has been criticised previously (Bergsteiner et al., 2010). The consensus of opinion however appears to favour the continued use of a zoomed-in grid with Kolb's offset datum (Kayes, 2005). Nevertheless, concern over the use of such a selective representation must be recognised. There is some evidence to support the claims that increasing exposure to VR over time promotes more active experimentation; that exposure to VR technology in the teaching and learning context appears to move the preferred learning style towards concrete experience; and that construction students have a stronger preference for active experimentation. However, that evidence is far from compelling in the broader context. It is certainly the case that specific learning style classifications are not apparent and this aspect requires further investigation.

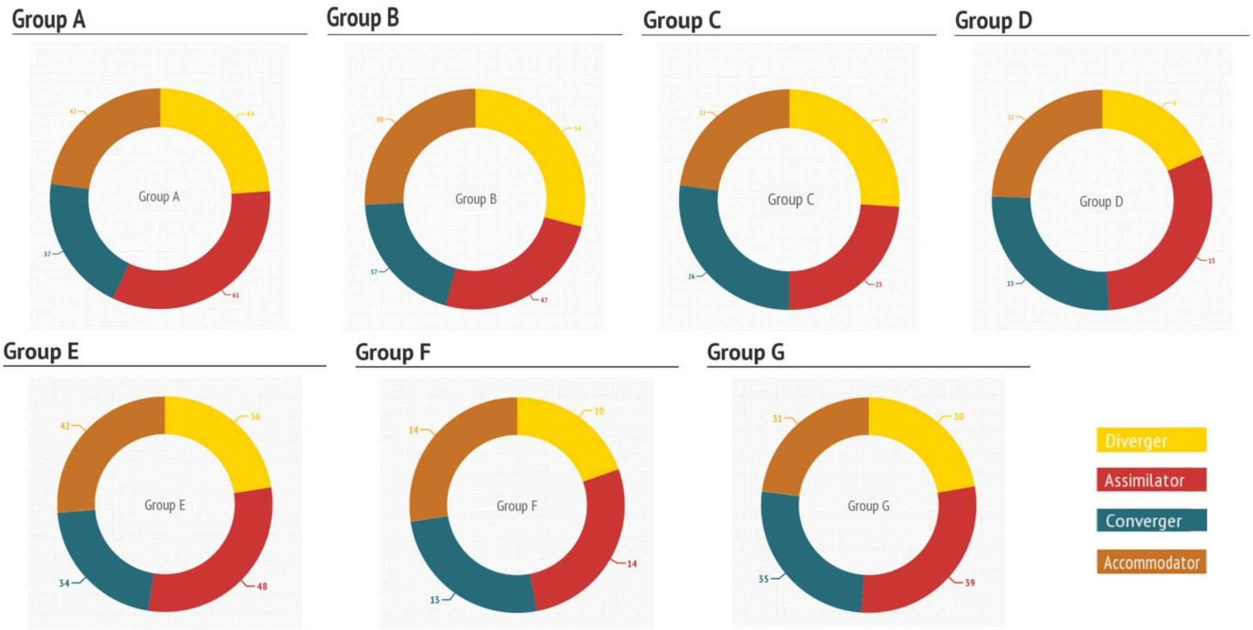

Figure 5: Learning style classifications for each of the seven investigations using a coloured donut representation

Figure 5 shows the proportions of each learning style in the seven investigations as a series of coloured donuts. The proportions are determined by the number of students in each cohort that preference a given learning style. The coloured donuts provide a novel way to visualise the learning style classifications specially developed for this research. The size of each colour on each donut in Figure 5 represents the proportional distribution of the four learning styles for each of the seven data groups. For consistency, each of the four colours representing the four different learning styles is located in the same quadrant/position as on the ELM grid (see Figure 1). This new form of representation makes it relatively simple to identify the majority and minority learning styles for each group. For example, in Figure 5 it is immediately apparent that for Group A the dominant learning style is Assimilator (red) and the minority is Converger (green). It is also relatively simple to make comparisons between groups. For example, in Figure 5 it is immediately apparent that Group B has the strongest representation of Diverger (yellow) learning style preferences of all seven of the groups. Most strikingly however, in all groups there is some degree of balanced distribution of learning style preferences. In other words, whilst there may be a bias towards the Assimilator learning style, this is not a significant bias. On the contrary, all learning styles are strongly preferred in all groups.

It is also apparent that no sequencing of Groups A, B and C is apparent; Groups B and E and Groups C and G are no more similar than any of the groups; and there is no apparent contrast with Groups D or F. This strongly indicates that exposure to VR technology, whether impacted over time or impacted immediately, does not appear to promote any radically particular learning style preference. On the contrary, the learning style classification is relatively evenly spread across all learning style preferences for all cohorts, regardless of exposure to VR or field of study.

If there is a relatively even spread of learning style classification, is there any more revealing spread of balance points for the individuals in each cohort? In this case the focus is on whether the spread of balance points reveals particular sub-groups within each cohort. In other words, are the individuals within a group clustered into specific learning style preferences or more evenly spread, and is the overall spread relatively tight or more dispersed. Clustering would suggest that other parameters are playing a significant role in the learning style preference. A tight overall spread would suggest that either the LSI instrument is failing to differentiate preferences or that there is actually little difference between individuals.

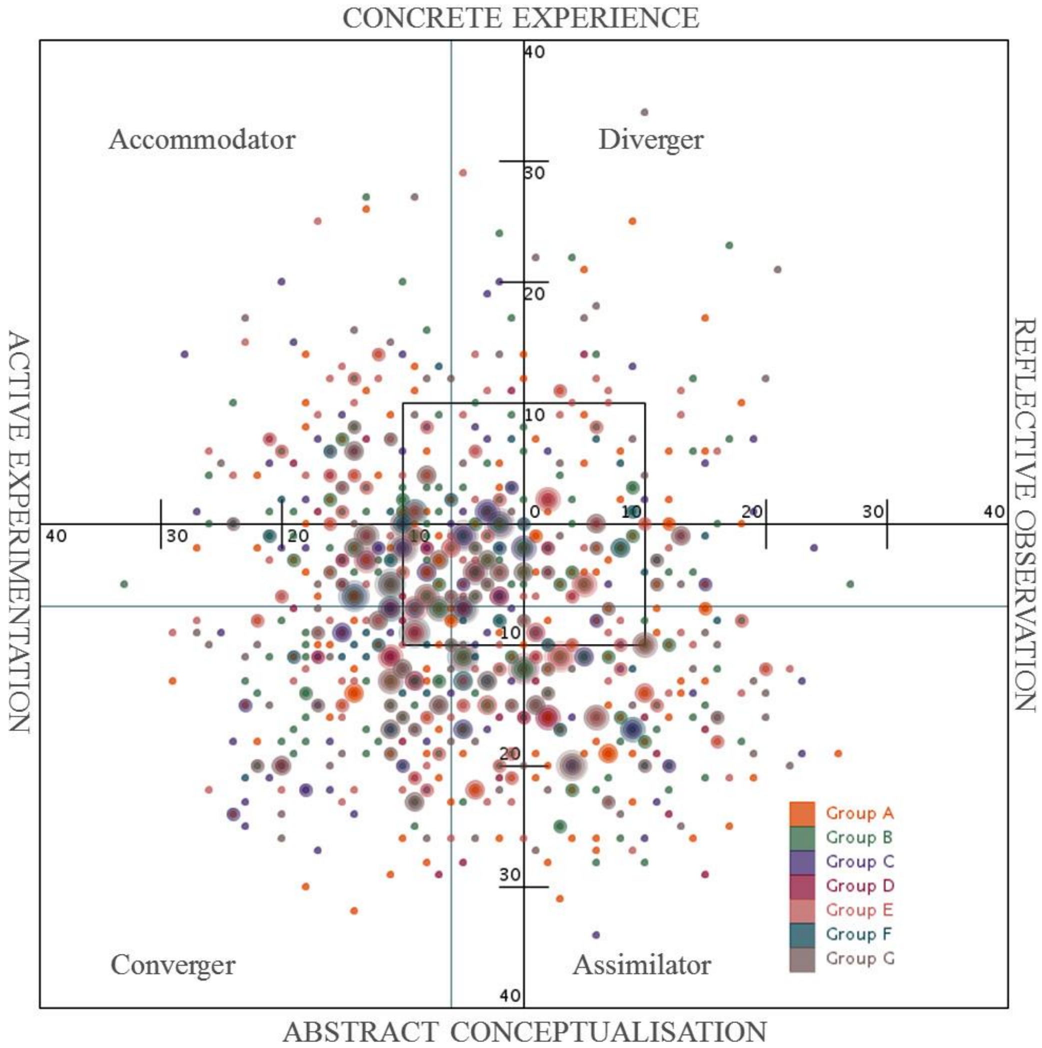

Figure 6: Individual balance points for all groups resented on a full LSI grid

Figure 6 shows the distribution of all individual balance points across the entire experiment presented on the full LSI grid with Kolb's offset datum indicated in blue-green lines. Each dot represents the learning style result for a particular participant. Where more than one participant is located at exactly the same position on the LSI grid, the dot size is increased. All dots are colour-coded to indicate the reference group of the individual. Equivalent plots for individual groups were also produced to confirm the consistency of the results. It is immediately apparent from Figure 6 that there is no significant clustering or stratification in the results. This suggests that the balanced classification revealed in Figure 5 is representative of each group and no hidden factors appear to be at play. It is also apparent that the spread of individual learning style preferences is widely dispersed. There are different individuals who represent extreme preferences (maximum scores of 36) along all four dimensions of the LSI grid. There are different individuals who represent extreme examples of each learning style classification (approaching maximum scores on two dimensions). This indicates that the LSI instrument is successful in differentiating both preferences and classifications of learning styles effectively at the level of each individual. Whilst there are different overall distributions of individual balance points for each group, the strongest and most consistent feature is well indicated in Figure 5, and that is the wide and evenly dispersed spread of individual learning style preferences.

CONCLUSION

Are there any grounds to support the long-held sense that the use of computers in general and VR in particular will condition (bias) the learning experience?

The findings of this research demonstrate that using a standard, zoomed-in representation of the LSI grid incorporating Kolb's offset datum (Figure 3), the longitudinal study of an architecture cohort in Phase One (2012) reveals that increasing exposure to VR over time promotes a progressive movement along and towards a preference for active experimentation. More broadly, Group D compared with all other groups reveals that exposure to VR technology in the teaching and learning context appears to move the preferred mode of learning along and towards a preference for concrete experience. Combined together, these trends indicate that use of VR will condition the learning experience towards an Accommodator learning style preference. This confirms the expectation that when virtual reality applications are used in teaching and learning, the learning behaviours will favour a more concrete experiential mode of learning and a preference for the Accommodator learning style.

Whilst any particular conditioning of learning style preference has the potential to stifle key aspects of a rounded learning experience, the promotion of concrete experience and active experimentation fit comfortably with the nature of professional degree programs such as architecture and construction. If the conditioning evident in Figure 3 is genuine, then the impact on learning and teaching in architecture and construction can most reasonably be taken to be a positive outcome for the use of VR. The key implication of this is that the introduction of VR technology into professional education programs of study can be encouraged because it promotes relevant learning styles.

In the broader picture of Figure 4, the classification of learning styles in Figure 5 and the individual distribution of balance points in Figure 6, the impression is far more of a balanced distribution of learning modes and learning style preferences. The wide spread of individual balance points evident in Figure 6 indicates that the LSI instrument is providing an effective representation of learning style preferences. The primary conclusion to be drawn from these findings is that all cohorts, whether exposed to VR or not and whatever the field of study, represent a relatively even balance on all four modes of learning and all four learning style preferences. Rather than conditioning the learning experience in any particular direction or conflicting with any existing learning style preference, exposure to VR technology supports a diversity of approaches and learning experiences. This is particularly noteworthy, as it contrasts with the implications drawn from Figure 3 and challenges any suggestion that existing architecture and construction cohorts adopt or prescribe a characteristic or particular approach to learning. Architecture and construction students do not privilege any particular mode of learning or learning style preference to any significant extent, but rather engage in all modes and represent all learning styles. The implication of this is that professional education students actually preference all styles of learning and all styles of learning should be supported and encouraged.

More particular to the study of experiential learning itself, several findings from this study are of significance. Whilst the consensus is still in support of using a zoomed-in LSI grid, magnifying differences can lead to questionable classifications and differentiation of learning styles between cohorts when considered in broader perspective. More significantly, the widespread practice of using a balance point to represent the averaged learning style preferences of a group can be considered utterly flawed. When the same data is presented using the novel visualisation techniques of Figure 5, very different conclusions can be drawn. When this is complemented with the display of individual balance points in Figure 6 it is very apparent that any differences in the balance points of group averages is inconsequential when compared to the differences/spread in the balance points of the individuals comprising those groups. In every cohort the spread of individual balance points were substantially greater than any spread between the group averages. The strong implication of this is that more judicious use of balance points is required, and wider use of visual representations such as Figures 5 and 6 is necessary. This is the first study to utilise the visualisation in Figure 5 and, apart from D'Amore et al. (2012), it is the only study to utilise the visualisation in Figure 6 to contrast individual with average group balance points.

LIMITATIONS AND FUTURE WORK

The subject of the research is specific to architecture and construction higher education at a single institution in Australia, and most participants were first year undergraduate students enrolled in these programs. All participants had therefore met a common, minimum entry standard including English language competency and regular academic requirements. From one perspective the fact that all participants were drawn from the same institutional context reduces the risk of variation in, for example, learning environment and teacher factors. On the other hand, limiting the source of participants homogenizes the population and the range of factors available for study. Future studies would usefully extend and contrast the sample population.

Although using this specific sample has certain benefits in terms of reducing the scope for independent variables, the use of broader and different samples in the future will enrich the scope and the depth of the research findings. For example, people from the architecture and construction industry with years of practical experience might have different learning style preferences, as could students from a different field of study. The representation of participants with different first languages and from different age groups in this study is also limited and further work in that regard would be relevant. Comparing participants across national and cultural boundaries could also reveal significant factors.

VR technology is itself still under development, and neither the definition of VR used in this research nor the particular implementation of the technology (The Situation Engine) are stable or comprehensive demonstrations of VR today or into the future. As alternative VR technologies emerge and VR becomes more deeply embedded in teaching and learning programs, studies of learning style preferences will be more representative than a single technology used in a particular way. The use of a single contrast group (Group D) to represent students with no exposure to VR is very limited, but the similarity of findings between all groups suggests that further studies should confirm a similar balance of learning style preferences. A primary focus for future research then needs to be on how learning and teaching can most effectively accommodate and support a variety of learning style preferences. This is perhaps where VR technology will not merely avoid promoting a single learning style, but positively accommodate and promote a full complement of learning experiences. The use of a virtual surrogate for experiential learning in the future might far better address the broad learning style preferences of our students.

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BIM-BASED QUALITY CONTROL FOR SAFETY ISSUES IN THE DESIGN AND CONSTRUCTION PHASES

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Abstract
Today's buildings are getting larger and more complex. As a result, the traditional method of manually checking the design of a building is no longer efficient since such a process is time-consuming and laborious. It is becoming increasingly important to establish and automate processes for checking the quality of buildings. By automatically checking whether buildings satisfy requirements, Building Information Modeling (BIM) allows for rapid decision-making and evaluation. In this context, the work presented here focuses on resolving building safety issues via a proposed BIM-based quality checking process. Through the use case studies, the efficiency and usability of the devised strategy is evaluated. This research can be beneficial in promoting the efficient use of BIM-based communication and collaboration among the project party concerned for improving safety management. In addition, the work presented here has the potential to expand research efforts in BIM-based quality checking processes.

Keywords: *openBIM, COBie, Evacuation, Safety, BIM-based Quality Checking, Automated Checking Module*

INTRODUCTION

As projects in the construction industry grow more complex, a wealth of information can be generated. Thus, interdisciplinary and systematic collaboration requires a considerable amount of communication and information transmission. Currently, the method for communicating information in design works has changed from paper-based drawings to three-dimensional (3D) Building Information Modeling (BIM), which enables efficient data management and quick decision-making. The BIM paradigm has been recognized as a potential catalyst for enhancing the productivity, efficiency, and collaboration of work in the construction industry.

At present, the construction industry has shifted from improving efficiency by reducing costs and project durations toward the issue of safety management (Kim & Park, 2011). With the increasing demand for safety management, Information Technology (IT), including safety management quality control, has emerged as an efficient solution because it can support human decision-making and evaluation. Specifically, IT solutions allow contractors to determine whether design solutions correspond to and satisfy safety management quality requirements. In a previous study, Wix (Wix, 2008) reported that 85% of architects and engineers have a high interest in automated rule-based checking because they spend more than 50 hours reviewing design solution models to ensure that they meet the requirements dictated by a building's functional, aesthetic, engineering, and environmental criteria.

*openBIM: openBIM is a universal approach to the collaborative design, realization and operation of buildings based on open standards and workflows. openBIM is an initiative of buildingSMART and many leading software vendors using the open buildingSMART Data Model including IFC (buildingSMART International. 2015).

BIM-based safety management improvement has been one of the primary topics of BIM research in the construction IT field. In most cases, BIM-based quality checking can be performed through the software itself so that building codes, zoning, legislation, and other requirements are satisfied. Quality checking during the design phase can improve design quality by detecting errors and omissions in building designs, while quality checking in the construction phase can improve the feasibility of a building's construction by detecting conflicts between various building elements or systems. Thus, the importance of BIM-based quality checking for safety management has been recognized because it allows for quick decision-making and improves the design and quality of construction in building projects (Seo, Kim & Kim, 2012).

Many researchers have suggested solutions for quality control in safety management. Kim et al. (Kim, Cho & Choi, 2010) developed a BIM evacuation simulation module, called InSightBIM™, for BIM-based quality checking in supertall buildings. Nisbet (Nisbet, 2014) proposed the Construction Operation Building Information Exchange (COBie) for both the exchange of asset information and the efficient management of facilities. The COBie can be used for safety management in that dangerous factors and decrepit equipment can be identified by the management system during the operation and maintenance of facilities. Zhang et al. (Zhang, Teizer, Lee, Eastman & Venugopal, 2013) developed an automated error-detection module and an installation system (i.e., fall protection installations such as staircases, slab edges, slab openings, and protective equipment) operated through Tekla™. In a case study, Seo et al. (Seo, Kim & Kim, 2012) proposed requirements (i.e., basic BIM modeling guidelines for use in architectural design) that considered the quality of BIM data. The efficiency of the BIM requirements were subsequently demonstrated when they were used along with the Solibri Model Checker™, a quality-checking tool. While a variety of systematic, BIM-based safety management methods and solutions were proposed in the above-cited works, the collection and identification of critical safety management factors was limited. In addition, it can be difficult to determine the efficiency of BIM-based quality checking for improving safety management when purpose-driven approaches are followed. Therefore, a formal and explicit BIM-based quality checking process for improving safety management is proposed in this paper. The efficiency and usability of the devised strategy is evaluated with case studies via an issue-driven practical approach.

QUALITY CHECKING AND SAFETY MANAGEMENT

Concept and characteristics of BIM-based quality checking

BIM-based quality checking can be considered as one of the quality management activities that exist in each phase of a project's life cycle. Therefore, it is important to define what quality checking is and compare a viewpoint of traditional quality checking approach with a BIM-based quality checking method. The Project Management Institute (PMI) defines quality management as follows (Project Management Institute, 1996):

Project quality management includes the processes required to ensure that the project will satisfy the needs for which it was undertaken. It includes all activities of the overall management function that determine the quality policy, objectives, and responsibilities and implements them by means such as quality planning, quality assurance, quality control, and quality improvement, within the quality system. Following a definition by PMI, quality control means both monitoring to ensure that the results of a specific project comply with relevant quality standards and identifying ways to eliminate the causes of unsatisfactory performance (Project Management Institute, 1996). In this context, BIM-based quality control can be defined as ensuring that business quality requirements are confirmed through automated (i.e., computerized) inspection and evaluation. BIM-based quality checking (Seo, Kim & Kim, 2012) is a platform for validating the design, construction, and other phases of BIM models from the viewpoint of quality control.

The quality of BIM models is influenced by both the designer's abilities and the tools chosen. Ultimately, the quality is reviewed with computerized tools because manual inspection is time-consuming and laborious. Thus, automated quality inspection is necessary to minimize errors and reduce the time spent on manual inspection. Recently, automated BIM-based quality control has been applied as a project-design quality improvement tool for scientific methodologies (O. K., 2009; Smith, 2008).

BIM is a rich and formal model that provides an ample number of possibilities for automated quality inspections; it can interpret and execute a variety of criteria ranging from client requirements to health codes, safety codes, and building design and construction regulations. The quality inspection process generally includes various phases according to the objectives and scope of a specific project. In general, the process is composed of four phases: rule interpretation, BIM model preparation, rule execution, and rule-checking reporting (Eastman, Lee, Jeong & Lee, 2009). Rule-checking tools such as the Solibri Model Checker™ (Solibri, 2015), Tekla BIMSight™ (Tekla, 2014), EDMmodelServerLite™ (Jotne EPM Technology, 2009), and Navisworks™ (Autodesk Inc. 2015) are commonly employed for BIM-based quality control. The BIM model can be validated with automated rule-checking tools because it is an object-oriented database with many types of building data. These tools enable physical, logical, regulation, and visualization inspection so that the quality of a BIM model can be validated.

Safety management and issues

The goals of safety management are to control safety actions and procedures in the workplace and to establish safety management processes (Benjaoran, Bhokha, 2010). In the construction industry, the main purpose of safety management is to prevent the occurrence of disasters on projects (e.g., accidents, injuries etc) and to control construction tasks by reducing construction times, wasted costs, and energy. Table 1 shows the general tasks associated with safety management in construction practice. These tasks include traditional and manual inspection activities. However, such processes are often time-consuming and laborious, and the approach depends on the practitioner's abilities and judgment. Therefore, computerized quality inspection is necessary to minimize human error and reduce inefficient time and effort spent on manual inspection.

Table 1: Work safety management tasks.

Safety Management Activity	Safety Management Issue
Self-management Safety Inspection Personal Protection Equipment Audit	Inspection & Observations
Risk Assessment	Work permit
Safety Education Emergency Information	Safety Training & Hazard Communication
Hazard Factor Management Warning Sign	Incident Management

In this section, the use of BIM technology is suggested to resolve safety issues at each phase of construction. Safety accidents in the construction industry may be diverse and complex in nature, accounting for a large proportion of the economic impact of accidents when compared with other industries. Countries and organizations can benefit from minimizing losses related to disasters, accidents, and worker injuries in all phases of design and construction (Ahn, Go & Lee, 1996). The use of BIM has the following potential benefits:

- Identification of possible flaws in construction
- Minimization of losses (costs, time, accidents)

In the design phase, BIM-based simulations can be used to evaluate safety and automatically check for adherence to regulations. Safety is ensured throughout the design phase via regular reviews of systems by safety professionals. BIM technology can be employed to address a range of issues in the design phase, including:

- Model-based pre-inspection of the safety of the environment
- Automated system inspection for adherence to safety regulations
- Facility and equipment safety plans associated with operation and maintenance
- Fundamental safety management using safety assessment checklists

Figure 1 shows an example of a simulated fire-escape inspection using BIM technology. The BIM model-inspection tool shows semi-transparent space objects, i.e., boundaries and openings such as doors and windows, as well as critical paths to the shortest escape routes.

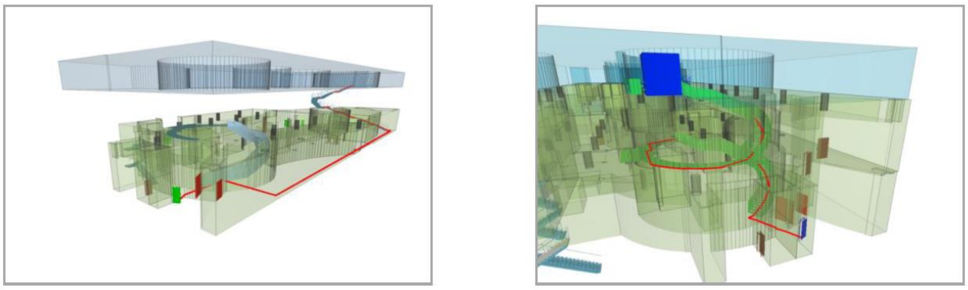


Fig. 1. Fire-escape inspection simulation using BIM technology.

The specific safety alternatives needed to control risks at construction sites vary depending on the construction process and associated project complexity. Safety information in the construction field can be inconsistent, and it is difficult to keep up with complex and fluctuating requirements (East, 2012). Some of the key safety issues during the construction stage are:

- Visually ensuring safety via 3D simulations
- Education for workers and managers through the use of simulations
- Minimization of construction errors and accidents

Figure 2 shows an example of a safety inspection in the construction phase. In a workplace, ceiling heights and delivery routes are significant safety issues because freight-loaded trucks and objects at elevated height, including Mechanical, Electrical, and Plumbing (MEP) elements or beams, can collide. The 3D BIM-model simulations in Figure 2 illustrate three possible types of collisions.

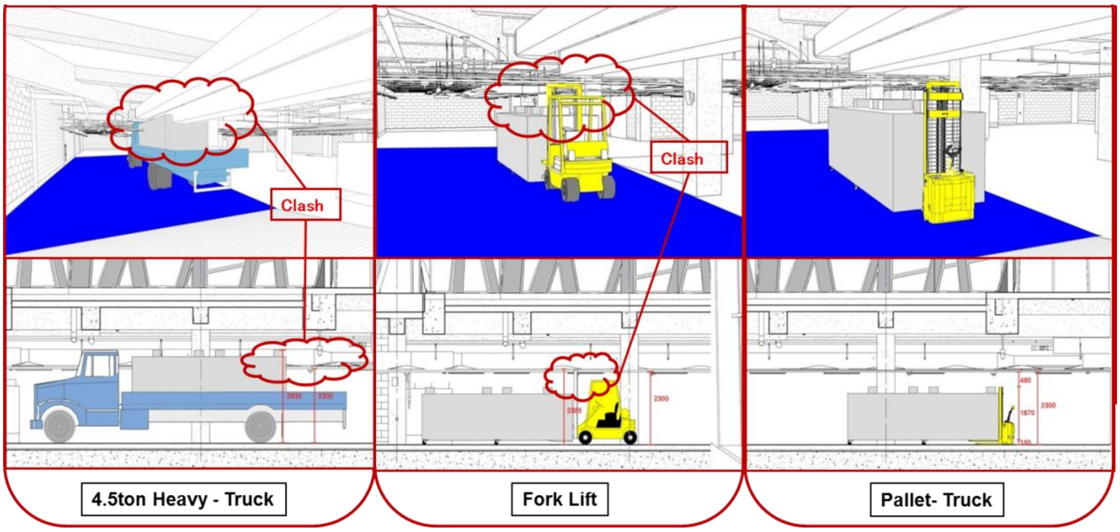


Fig. 2. Safety inspection using collision simulations.

CASE STUDIES ON SAFETY MANAGEMENT

In this work, various cases associated with safety issues are reviewed. In particular, cases related to developing applications, making modeling guidelines, and analysing regulations and standards for Facility Management (FM) are examined.

Fire evacuation in skyscrapers

As buildings become larger and more complex, the process of reviewing every part of a building for conformance to regulations is growing increasingly more difficult. Automated evacuation-inspection systems are necessary for simulating a review of supertall buildings (skyscrapers), and BIM can be used for the identification of optimal evacuation egress (Kim, Cho & Choi, 2010). Figure 3 shows the development and validation of an evacuation-simulation module in an integrated BIM-based quality inspection system called InSightBIM™ (Seo, Kim & Kim, 2012). First, evacuation regulation and application criteria were analyzed for BIM modeling. The translated BIM model in Industry Foundation Class (IFC) format is reviewed using the quality inspection tool, which consists of three modules (analysis of egress options, analysis of emergency elevators, and analysis of evacuation safety zones). The analyzed results are ultimately output into XML format, allowing users to check for errors corresponding to the safety issues of egress, evacuation, and emergency elevators.

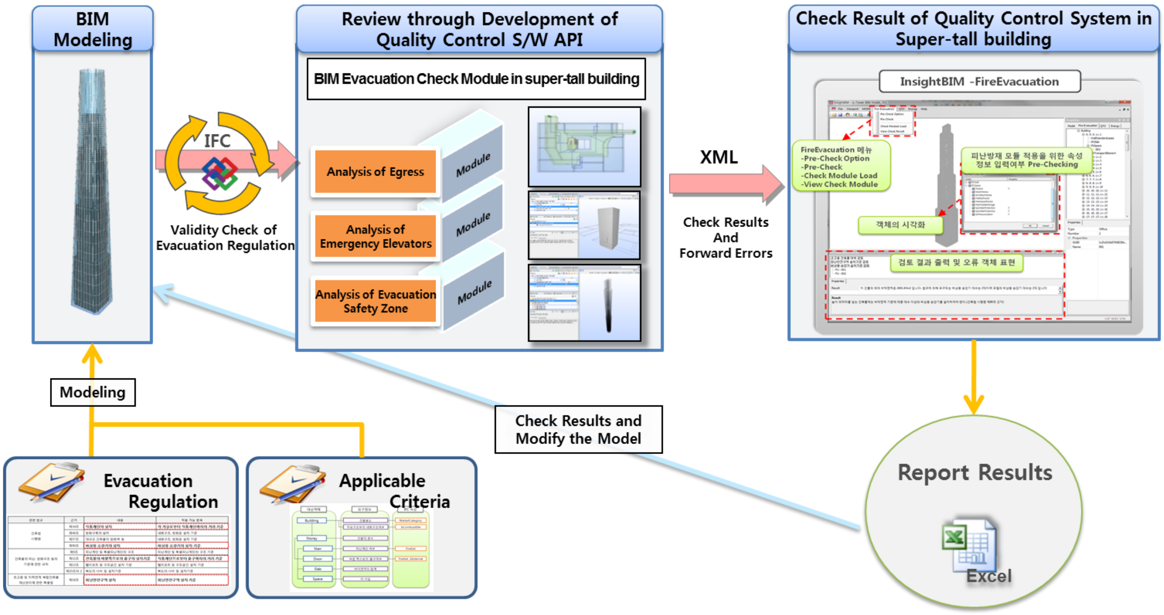
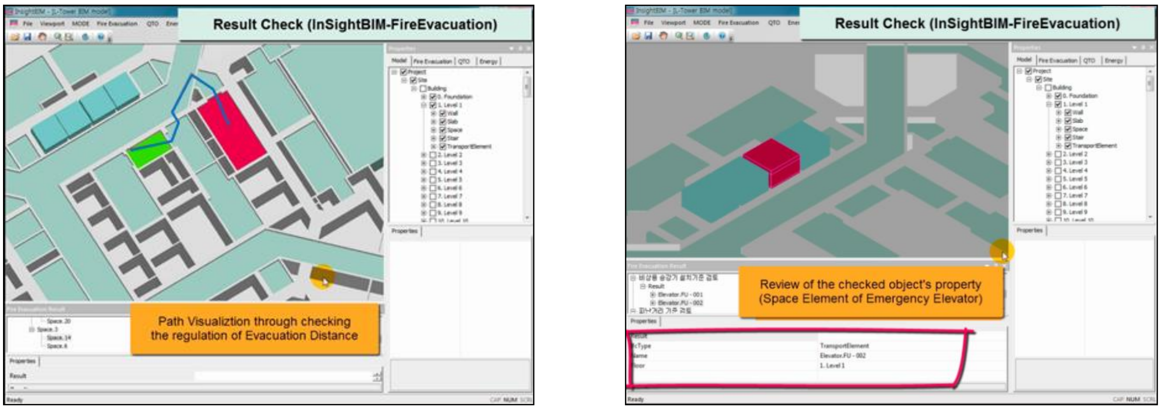


Fig. 3. Development and validation of a BIM evacuation-simulation module.

Emergency elevators and evacuation safety zones can be checked automatically using the egress route module (the Application Programming Interface [API]). This module operates according to the following process:

(1) Develop a module to check for egress routes using the Java™ programming language
(2) Review the evacuation egress route, emergency elevator, and evacuation safety zone criteria using developed rule-sets
(3) Execute rule-checking (InSightBIM™-FireEvacuation)
(4) Report results (visualized error lists)



(a) Path visualization of the evacuation distance inspection

(b) Results of the evacuation elevator inspection

Fig. 4. Example of InSightBIM™-FireEvacuation software.

Safety management is reviewed using InSightBIM™–FireEvacuation. The inspection results pertaining to the building's shortest egress route and emergency elevators are shown in Fig. 4(a) and (b), respectively. Through this work, the following goals can be achieved (Kim, Choi & Cho, 2013):

(1) Attainment of efficient and accurate safety information (emergency/safety zone/evacuation egress routes) during the design phase
(2) Planning for accurate safety management.

As an example, consider skyscrapers - these have many floors and spaces, where automated inspections would be very powerful in that these would allow for rapid and precise results to be obtained. In addition, both vertical and horizontal pathfinding for evacuation would be significant research topics for future projects.

COBie

The COBie is a data schema for exchanging BIM data in the facility management phase (Park, 2015). The necessary information (e.g., materials and properties) are stored in spreadsheets. COBie makes it possible to assess safety management data through a review of a building's energy savings and efficient facility management. The outline of COBie is as follows:

(1) COBie is a data format for managing and using asset information in the facility management phase.
(2) IFC data converted from BIM data is stored in spreadsheets so that it is easily accessible in the facility management phase (Lee, Yu & An, 2012).
(3) COBie focuses on delivering building information rather than geometric modeling, and it is a subset of a BIM model.

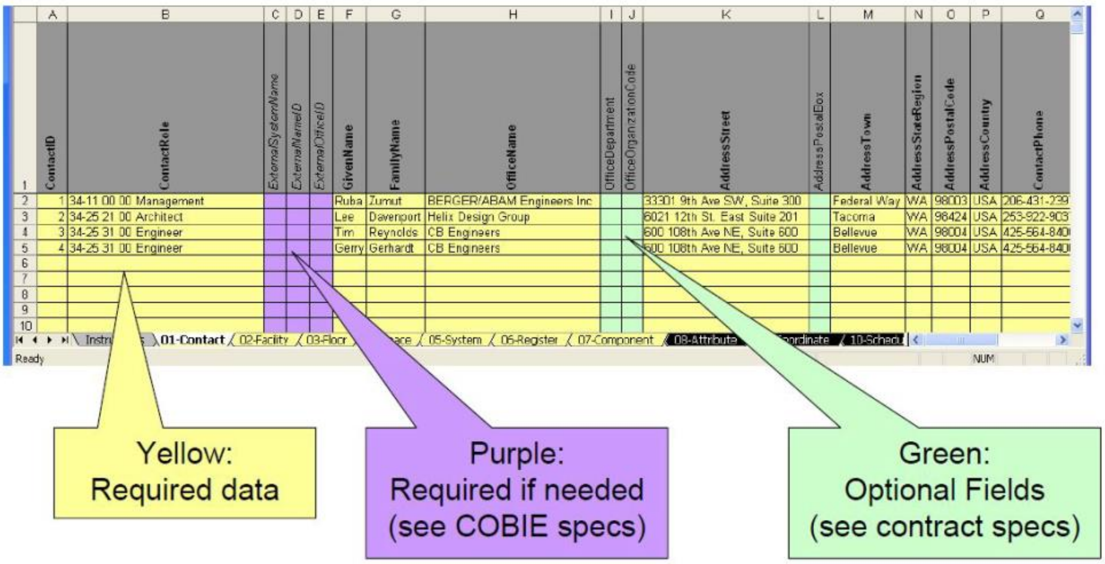


Fig. 5. Example of a COBie template (East, 2012).

COBie can be used to document product data to support specification, selection, and replacement processes (Nisbet, 2014). The COBie template contains 16 worksheets for information on contracts, the facility, floors, spaces, zones, components, systems, parts, resources, jobs, documents, attributes, coordinates, connections, and issues. In the facility management phase, the most active uses of COBie are:

(1) Building and maintaining energy-saving and energy-efficient facilities by converting COBie data into the ifcXML format via a data converter
(2) Pre-maintenance of facilities and safety precautions through the efficient management of COBie data

COBie's data collection method is based on process-oriented representation. Thus, the end user or manager does not have to wait until the end of a project to receive data. Data are inputted by experts working directly in the field or automatically by the BIM software. Both processes are efficient for collecting precise facility management data. Although COBie must be localized so that it can adapt to each country's construction environment, it can still reduce costs and time for facility management maintenance.

Automated safety inspection of construction models and schedules

According to regularly published safety studies, the number of employee injuries and deaths from falling increases every year in the United States. The objectives of one BIM-based safety research project was to analyze simplified rules and develop an automated detection and installation system (Zhang, Teizer, Lee, Eastman & Venugopal, 2013). The authors classified the rules for fall protection into three parts: building objects, object attributes, and prevention systems, as shown in Figure 6.

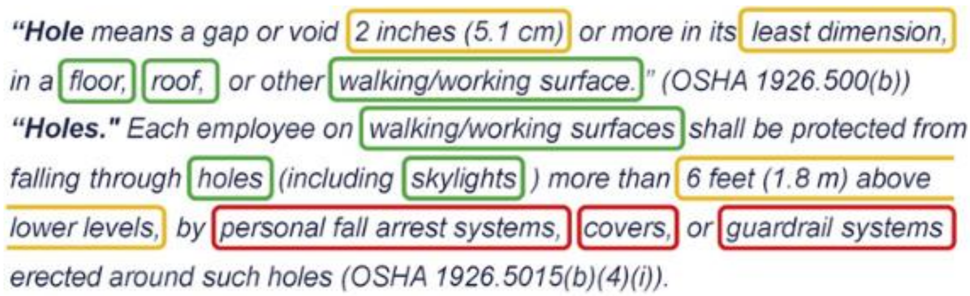
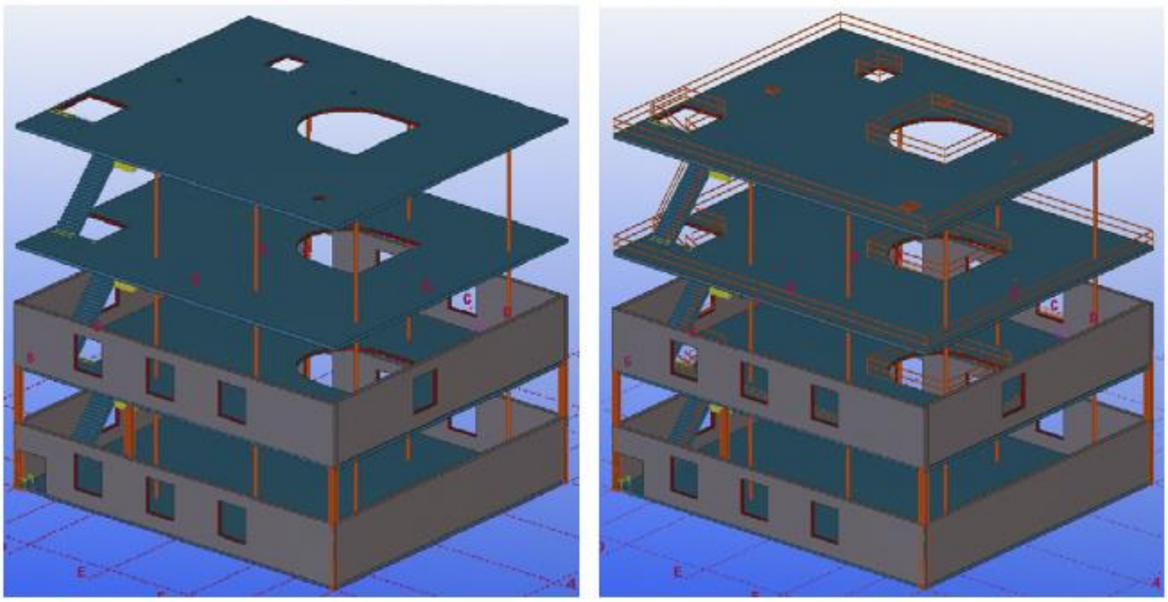


Fig. 6. Example of rule simplification for fall protection (green = building objects; orange = object attributes; red = prevention system).

The system can automatically install protective equipment for staircases, slab edges, and slab openings with different shapes and dimensions.



(a) Modeling without a protective system (b) Modeling with a protective system

Fig. 7. Automated rule-based fall protection detection and installation in Tekla™.

Case study results

A variety of methods and solutions for safety management in a computerized environment have been proposed in previous studies. As such, many of the customary practices performed informally during the construction process have been eliminated. Table 2 outlines the major aspects of previous research related to safety management.

Table 2: Summary of previous safety studies.

Subject	Applied phase	Safety issue	Applied method	Result deliverable
Fire evacuation in a skyscraper	Planning	Fire evacuation pathfinding simulation	Rule-based quality control for egress route	Modeling guide and application development
COBie	Facility management	Safety management using FM DB	ifcXML format using spreadsheets	Standard proposal
Automated safety inspection of construction models and schedules	Planning and design	Fall protection detection and installation	Automated rule-based modeling revision	Application development for revising model

Each of the above-cited studies can be considered as cases for improving safety management based on their purpose-driven approaches. However, it can be difficult to determine the efficiency of BIM-based quality inspection from such research, and the tasks of collecting and identifying critical factors for safety management can be complex. Therefore, the purpose of this study is to use an issue-driven approach to determine the efficiency and usability of safety management quality-inspection processes and applications.

BIM-BASED QUALITY CONTROL FOR SAFETY ISSUES

Typically, there are three kinds of categories for BIM-based quality control (Choi, 2012). First category is physical quality control. It means duplicated elements checking, clash checking between physical elements on different construction domain such as structure and MEP and so on. Second category is logical quality control. It means rule-based checking using formulas, architecture acts, guidelines, specifications and so on. Last category is data quality control. It means data reliability checking. It determines whether specific component has its own proper attributes or not. For example, a door has to have not a slab's attributes, but door's attributes. In this paper, using various BIM checking tools, we executed quality inspection about space, architecture, structure, site and MEP model by common rule-based and visualization-based checking methods.

Quality inspection process

A BIM-based quality inspection process was devised to ensure the quality of both individual, independently developed models as well as models after integration. First, the space model was checked to confirm that the code was adequately satisfied. A second round of checks were performed for the BIM models developed after this stage, as well as for the architecture, structure, and MEP models. These checks were based on BIM-based quality criteria specific to each stage. After the quality of each model was assured, the integrated model was the subject of a coordination inspection so as to confirm that the critical elements in each model were well coordinated without colliding with any other elements.

Issues that arose in the inspection were addressed at a meeting of all team leaders in order to determine who was responsible for all specific issues and how best to resolve them; the process was repeated until all important issues were resolved. Through this process, a final decision was delivered to the technical members so that the models could be updated. Consequently, high-quality BIM data and a final model that was assumed to contain all information necessary for the construction and maintenance phases were produced. Figure 8 shows the overall BIM-based quality control inspection process for safety issues.

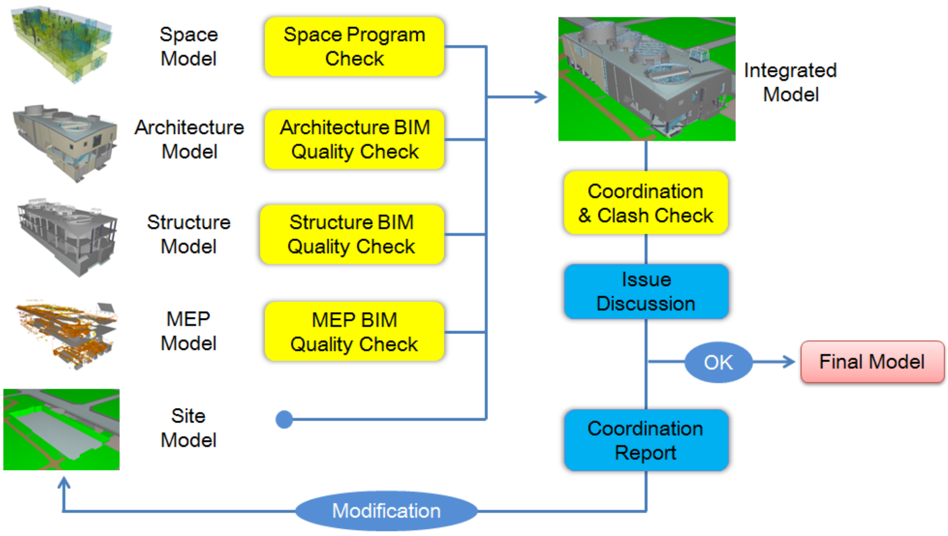


Fig. 8. Process for BIM-based quality control.

Case overview

The Ecology Learning Center at Pangyo was employed as a sample project to explain issues related to safety management (PEN Build Korea, 2012). Even though, this is an initial project about BIM-based safety management, it is meaningful because it shows various possibilities of BIM adoption about an automated inspection and evaluation. This project was carried out by PEN Build Korea and POSCO E&C Associates for the BIM and Safety Competition in Singapore. As a joint venture in this competition, PEN Build Korea and POSCO E&C Associates consisted of BIM-related professionals and BIM coordinators, including architecture, structure, MEP, sustainable design, construction cost, operations and maintenance, and virtual reality professionals. The authors participated in the competition and developed a BIM-based quality inspection process. The Ecology Learning Center was selected for the following purposes:

(1) To establish a public community center in response to urban sprawl around the Pangyo area
(2) To create a green junction connecting a nature-friendly water system to nearby ecological infrastructures such as water-restoration facilities, waste-incinerating facilities, and energy facilities
(3) To enhance quality of life by sharing a creative space for experiences, exhibitions, education, and so on.

The Ecology Learning Center is located at the Housing Development District No. 8 Vicinity Green Park in Pangyo. Urban programs proposed around the site address issues related to ecological infrastructure, ecology learning, youth, and culture. Thus, the project sought compatible programs that fit the urban context; this exhibition was suggested as one of those programs.

The building has an area of 1,892.73 m^2, a Gross Floor Area (GFA) of 4,568.90 m^2, and a height of 19.88 m based on an average ground base level of +40.08; 35 parking lots are proposed for the site (see Table 3).

Table 3. Pangyo Ecology Learning Center project summary.

Project		Pangyo Ecology Learning Center	
Location		Pangyo Housing Development District No.8 Vicinity Green Park	
Region/District		Natural Green District	
Site		No.8 Vicinity Green Park	119,879 m^2
		Proposed Area	3,195.30 m^2
Function		Culture & Exhibition Facility	
Volume		B1F ~ 2F	
Height		19.88m (Based on Average Ground Level +40.08)	
Structure		RC, SC	
Main Exterior Material		Exposed Concrete, Gabion Wall, Stainless Steel Mesh	
Street Condition		20m Planned Street in the Front	
Building Area / Gross Floor Area		1,892.73 m^2 / 4,658.90 m^3	
Coverage Ratio / Floor Area Ratio		1.58 % / 2.36 %	
Parking	Code	6 Lots above Ground (Incl. 1 Handicapped Lot)	
		29 Lots underground (Incl. 1 Handicapped Lot)	
	Proposed	35 Lots	

Safety management in the design phase

In order to check for safety issues in building projects, two views were considered. The first was the viewpoint of the construction workers so as to address any possible safety issues during the construction phase. The purpose of safety inspections should be to prevent accidents during construction and reflect the BIM-based accident prevention recommendations from the design phase. The second view was that of the building's users after construction. These safety issues would relate to any potential disasters experienced during the building's use. Here, the purpose of the safety inspections was to minimize the potential harm to humans if accidents occurred. In particular, BIM enables preliminary reviews through its visualization and simulation tools because they contain a great deal of building information that can be used for safety management improvement alternatives. This section introduces critical safety management issues in the design phase; specific safety issues will be discussed later.

Issue – deficient elements

One safety issue in this case related to missing elements. Depending on the case, deficient elements could lead to serious safety problems such as falling or collapsing. This was especially critical during the construction process as well as for the structural safety of the building after construction. Using the Solibri Model Checker™, a missing stair slab was noted, which was subsequently revised in the model.

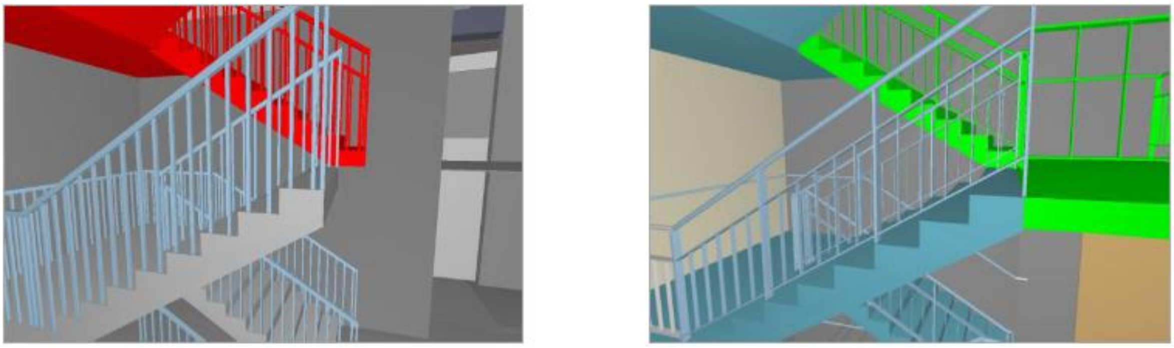


Fig. 9. Deficiency issue: missing stair slab identified; issue resolved by adding a slab.

In this case, each object must have the correct building attributes; otherwise, information can be lost due to errors in translation to other file formats. Therefore, the property of each building object must be validated before inspection.

Issue – falls

Falls often occur around floor and roof openings and can be a serious issue for humans working at these edges when they are exposed to the weather. A unique way of preventing falls of these types is to install temporary safeguards or railings around dangerous locations. BIM should be able to provide additional information regarding this issue. Figure 10 shows a floor opening that raises a safety issue, which BIM could prevent by recommending the addition of temporary railings around the opening.

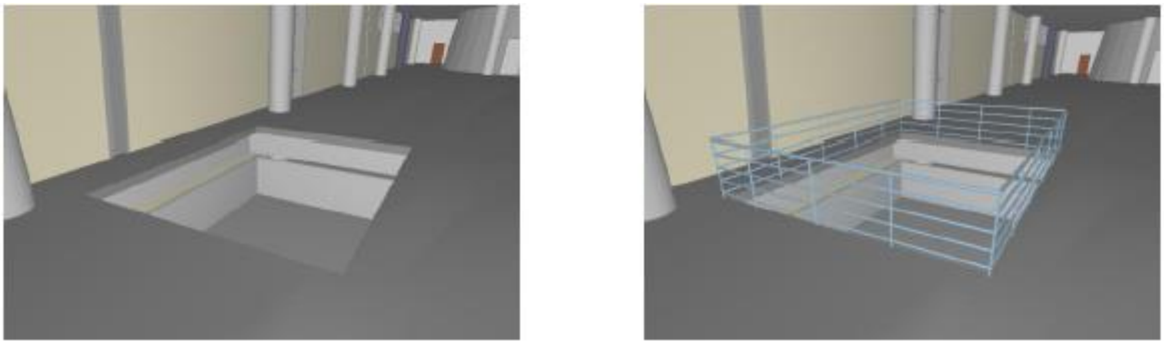


Fig. 10. Fall issue: floor opening has no ramp; railing is added.

Although the authors revised the model manually after inspection, an API, which is capable of revising the BIM model automatically, could have generated precise architectural objects such as railings and fall protectors.

Issue – fire

Fires are one of the main safety issues for building users after the construction of a building is complete. In order to prevent the occurrence of a fire, sufficient information should be modelled and added into BIM. Such information includes firewall properties and fire zone data. Firewall properties should be composed of proper safety materials. Figure 11 shows a building with proper zones and firewall information identified as providing protection against fire accidents. In addition, fire escape traffic distances and fire zone area allocations are the biggest issues with regard to fire safety. The proper parameters for the above issues are mandated by building codes for fire security. This visualization information can be linked with real-time monitoring for safety management in later phases.

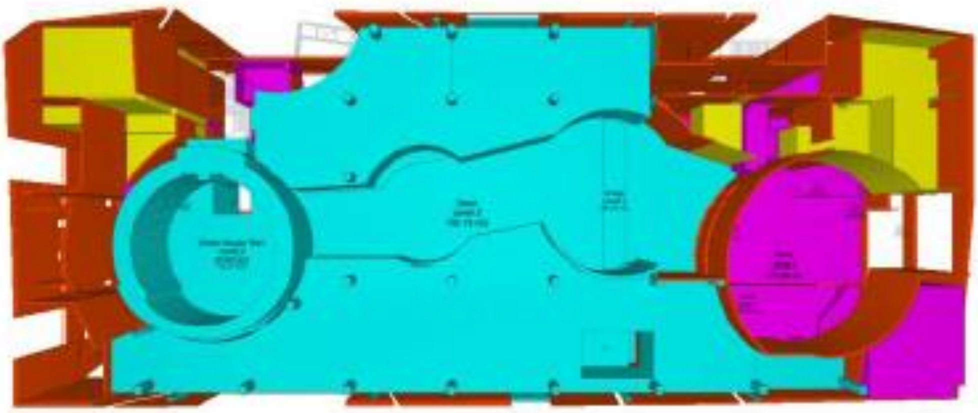


Fig. 11. Visualization of fire zones and walls for safety.

Issue – health accident

Finally, to secure the safety of the MEP facilities, an inspection was performed to confirm that there was sufficient safety information (Figure 12). This information included data pertaining to hazards for building users, such as pipes pumping noxious materials into the building or water pipes passing near power lines. The existence of this information in BIM itself provides a way of preventing possible disasters through proper visualization.

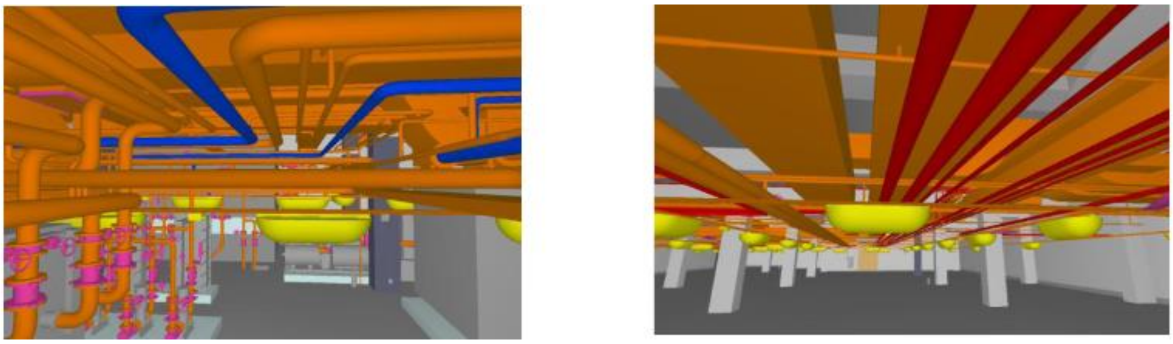


Fig. 12. Safety issue: pipes carrying noxious materials, water pipes near power lines.

In the design phase, one of the most important quality inspection methods is 3D visualization, as illustrated in the above examples. Depending on the colours used to reflect the building's components, building users can be aware of safety zones as well as evacuation paths in advance.

Through BIM-based quality inspection in safety design, safety issues such as clashing elements and possible collisions, falls, fires, and health-related accidents were resolved.

Safety management in the construction phase

There are a certain number of hazard factors in the construction field. In this study, strategies to reduce the possibility of a disaster occurring during work were discussed. A decision was made to apply the visualization and simulation techniques featured in BIM. One of the efficient characteristics of BIM is its methods for simulating construction planning, fall protection, steel element prefabrication, and other aspects of construction in advance. Here, safety simulations with BIM-based quality inspection were performed in Navisworks™ and Digital Project™. The critical issues of safety management in the construction phase and all identified safety issues are presented in the discussion section.

Issue – excavation safety inspection

An excavation simulation was performed based on the total volume of earth from the BIM data and the efficiency ratio of machinery to time (Figure 13). The risks associated with actual construction compared with the construction planning schedule were mitigated through the use of BIM simulations in Navisworks™ based on the earthworks plans for the construction site's safety, and working environment needs. Risk control of the excavation was monitored based on the work schedules of two backhoe loaders (0.7 m3) and dump trucks. We present the results obtained in Navisworks™. This simulation used inputted work schedule information and made it visual, but a method for calculating the amount of excavated land based on the BIM model's land attributes should be researched in a later phase.

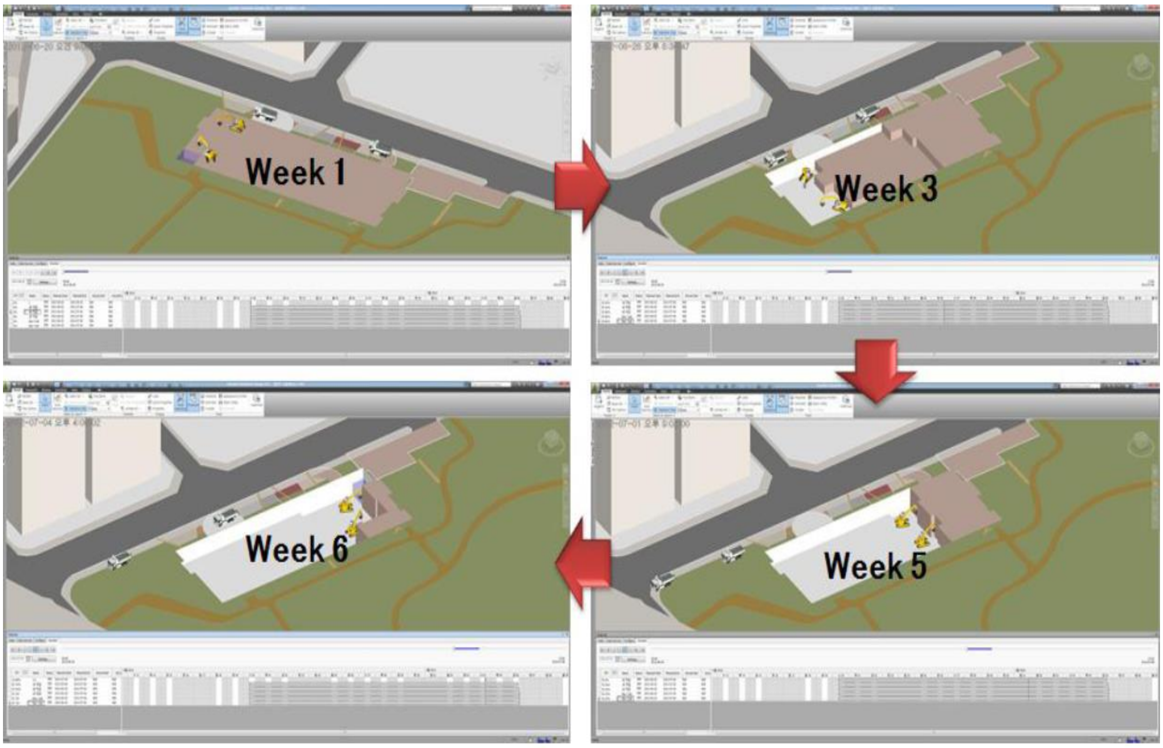


Fig. 13. Excavation safety inspection.

Issue – steel fabrication check

To provide detailed information for steel fabrication, a 3D model was created in Digital Project™, and Numerical Control (NC)-code was extracted by unfolding for steel-pipe cutting. Figure 14 shows the steel fabrication process employed in this project. For the fabrication simulation, unfolding steel pipe was modelled in Digital Project™, and NC-code was extracted for Computer-Aided Manufacturing (CAM). Using the NC-code, the steel pipes were cropped safely in the factory. Based on the case illustrated below, an excavation simulation and prefabrication can minimize risks and accidents at construction sites. This type of modeling and inspection using BIM models can help improve safety during and after construction because excavation and steel welding are not always planned out in advance.

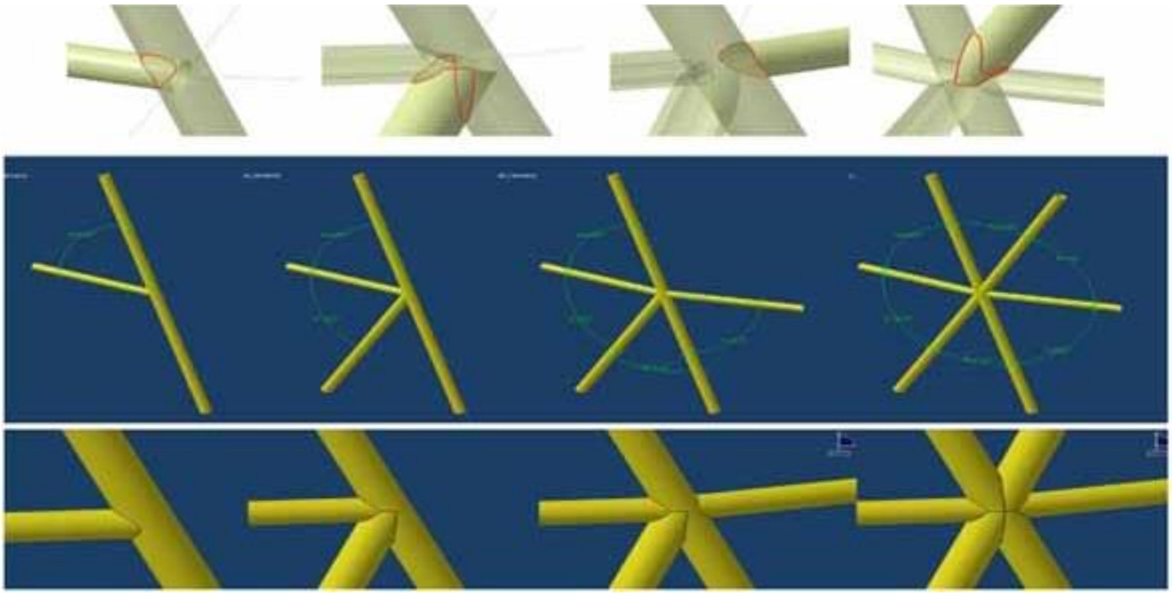


Fig. 14. BIM modeling and process for steel fabrication.

Discussion

During the project, team members (including the authors) investigated and analyzed items required for safety management in the design and construction phases. A checklist was defined and quality inspection was performed using BIM tools such as Vasari™, the Solibri Model Checker™ (SMC), Navisworks™, and others. Shown in Table 4 are the team members' resolutions of the safety issues. Quality inspection and revised BIM models were executed using several rule-checking tools until the team members were satisfied with the levels of safety.

The team members were satisfied with the proposed methods because significant improvement were observed when compared to conventional strategies (based on manual inspections that depend on a practitioner's ability and judgment). The results indicate that traditional practices make it difficult to identify and control safety issues; most members currently participating in the project could not explore a computerized approach that continuously identified safety management issues and controlled decision-making via the proposed processes with the devised quality-inspection tools. As a result, it was found that the proposed process and its application can be more effective than current customs and practices in terms of improving safety management.

As highlighted in Table 4, several safety management issues result "Partially satisfied" and must still be resolved. In terms of deficient element inspections, there can be no errors in the design, intent, and rationale for element objects. For example, a wall object should be placed such that it is connected to two floor objects in rule base, but if the wall has no structural problem, there can be no modeling error. This problem was encountered quite often during the case study. Therefore, various types of problems that are not design errors must be collected and classified in detail; this scenario arises due to the functional limitations of SMC.

Table 4: Quality inspection list for safety management.

Phase	Safety Issue	Objective	Method	Results
Design	Space program inspection	Finding unallocated area and arrangement	Space validation in SMC	Satisfied
	Clash elements inspection	Removing duplicated elements	Clash check in SMC	Satisfied
	Deficient elements inspection	Modeling revision	Deficient check in SMC	Partially satisfied
	Collision inspections	Securing enough space	Collision check in SMC	Satisfied
	Inspection for falls	Adding safeguards (fence, railing, etc.)	Rule-based check in SMC	Satisfied
	Inspection for fires	Securing firewalls and evacuation routes	Rule-based check in SMC	Partially satisfied
	Health accident inspection	Securing MEP safety	Visualization in SMC	Satisfied
Construction	Preliminary cost estimation	Effective budget planning	Simulation in Navisworks	Satisfied
	Excavation simulation	Planning work period and path	Simulation in Navisworks	Satisfied
	Concrete deposition simulation	Concrete QTO calculation and depositing plan	Simulation in Navisworks	Satisfied
	Fabrication simulation	Steel-pipe cutting and welding	Modeling using Digital Project	Satisfied

In the case of a fire safety inspection, secure firewalls and evacuation routes are important aspects of fire safety. Firewalls were checked for their material information, and spaces were checked to ensure that they had evacuation routes. Here, one of the main issues is determining the optimal distances and sufficient times for the building's users to be able to escape from anywhere in the building to safe places. Such an issue can be resolved by developing rule sets in the SMC and applying local codes.

In addition, the BIM model data obtained in this case study were translated into openBIM (IFC data format), and IFC data were used for data exchange between the BIM modeling and quality inspection tools. However, the problem of data loss from limited interoperability between application tools during the case study persisted. Therefore, as one of a number of alternative methods, detailed guidelines that can enhance data interoperability between application tools based on their various uses must be developed.

CONCULSION

This paper discussed the efficiency and usability of safety management through the application of a proposed quality inspection process. As a result of the case study, it was found that this proposed method can be used efficiently for safety management, which indicates that current customs and practices (following traditional and manual inspections) still make it difficult to carry out a preliminary safety management review.

However, when carrying out our proposed process, problems caused by data interoperability among the design and quality-inspection tools remained as critical obstacles to improving safety management in a computerized environment. The errors discovered during quality inspection are categorized into several types, including building element clash, building element overlap, and escape code. The results also indicate that the adoption of BIM has not yet reached a sufficiently high level to enable its practical use.

Quality control for safety management is very important in that it prevents possible disasters and accidents based on preliminary reviews. In particular, BIM provides rich and formal descriptions, which in turns allows for the possibility of automated quality inspection for improving safety management. The goal of BIM-based quality inspection for safety management was to identify the best ways of minimizing the dangers to humans and eliminating risk factors in the life cycles of buildings.

BIM-based quality control and inspection for safety management can be dependent not only on modeling methods and skills, but also on the performance and interface of applications. Further research will be conducted in this area so as to improve process efficiency (including data interoperability among applications, decision-making, etc.) in real projects and to develop BIM-based quality guidelines for safety management.

ACKNOWLEDGEMENTS

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TOWARDS A THEORETICAL FRAMEWORK FOR HBIM APPROACH IN HISTORIC PRESERVATION AND MANAGEMENT

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Abstract
In the context of rapid technology development, the theory of using building information modelling (BIM) has been used in several historic places. With BIM technology, an accurate virtual model of a historic building is digitally constructed in order to maintain the building through its entire lifecycle, including demolition. This model, known as historic building information modelling (HBIM), represents a new paradigm within architectural heritage that can be used for creating, conserving, documenting, and managing complete engineering drawings and information. Therefore, the aim of this paper is to give an overview of the concepts, as well as surveying and representation techniques that are used in HBIM in order to support the process of further integration and demonstrate how the complexity of built heritage resources can be dealt with. In addition, the study presents a theoretical framework that has been constructed as a guide towards understanding the different aspects of historic preservation and management through a smart open platform.

Keywords: *BIM; Documentation; HBIM; Historic; Surveying; 3D modelling*

INTRODUCTION

Construction projects are becoming more and more complex and difficult to manage. One complexity is the cross interdependencies between stakeholders such as financing bodies, authorities, architects, engineers, lawyers, facility manager, and occupants. However, during the last decade, a major shift in information technology in the construction industry has been caused by the creation of building information modelling (BIM), known in academic circles as the new computer-aided design (CAD) paradigm (Azhar, 2011; Bryde et al., 2013). BIM is a relatively new technology that will grow to play an even more crucial role in design, construction, and maintenance of buildings. It has been defined as a set of interacting policies, processes, and technologies that generate a methodology to manage the essential building information in digital format throughout the building's lifecycle (Succar, 2009; Succar and Kassem, 2015).

In the field of conservation of heritage buildings, a method linked to documentation and management of historical buildings is required to carry out regular maintenance. In the last decade, many traditional surveying methods have been used to record and represent these buildings. From there, it is a logical step to have an instrument that allows collection, comparison, and sharing of all the available data of a building, wherein future information about maintenance or restoration activities can be added (Murphy et al., 2013; Oreni, 2013). In this context, this paper discusses the feasibility of moving from the traditional representation and 3D content models to the so-called historic building information modelling (HBIM) approach. This integration of heritage recording and BIM is now a method to document and manage historic buildings, in which parametric objects are built, taking into account historical data, and layered-in plug-in libraries represent building components, including both geometric and non-geometric attributes and relationships (Dore and Murphy, 2012; Volk et al., 2014).

The HBIM approach is a new one, as most BIM applications are used to design new buildings and now play an important role in historic preservation and management. Based on current academic literature documenting the use of HBIM, the aim of this paper is to analyse the tool from an architectural point of view and present a theoretical approach to understand and document the HBIM approach for historic preservation and management.

RELATED WORKS

After reviewing the existing literature, both academic and professional, revealed two different approaches in dealing with HBIM implementation. The first approach delineates the HBIM process that illustrates in detail the surveying technologies and modelling processes used to visualise historic buildings, and it has been presented following different approaches (Stefano, 2015). This approach has mostly been studied by computer science and information systems researchers. However, more recently, studies have been conducted by architecture or built environment researchers (e.g., Arayici (2008), Brumana et al. (2013), Bryde et al. (2013), Dore and Murphy (2012), Fai and Rafeiro (2014), Garagnani and Manferdini (2013), Quattrini et al. (2015)).

In the other scientific approach, several works have dealt with HBIM from a broader view via the Architectural, Engineering and Construction (AEC) industry. Many such works have discussed and framed BIM processes, concepts and policies. The most important works include those conducted by Succar (2009; 2010), Jung and Joo (2011), Porwal and Hewage (2013), and Kassem et al. (2015). However, their theoretical frameworks were created mainly to review BIM-focused, rather than HBIM-focused, knowledge.

In view of the above, the current knowledge still remains significantly insufficient. It was noted that a comprehensive architectural viewpoint was missing from the existing literature. To address this gap, the paper merges these related approaches and positions them as a theoretical framework to understand the HBIM approach and summarise its processes, technologies and policies.

RESEARCH METHODOLOGY

In order to present a comprehensive architectural viewpoint and to support the multidisciplinary thinking, the study develops a theoretical framework which is dependent largely upon published literature and supported by secondary sources. This review of existing literature of HBIM implementation covered a collection of processes, concepts and policies, in which information was assembled, analysed and discussed as a guide towards understanding the different aspects of historic preservation and management.

In view of the above, the study first introduces BIM origins, its evolution and the multidimensional models of BIM. Second, it provides an overview of the most recent surveying methodologies and HBIM processes that may be of benefit to architects in historic preservation. Third, it proposes a theoretical framework for management and historic preservation by articulating issues regarding the concept of HBIM in the AEC industry. Furthermore, this paper discusses the anticipated potential of HBIM to support historic conservation and information sharing for professional users, institutions and experts involved in decision-making processes.

LITERATURE REVIEW

Recently BIM-focused knowledge is a huge topic that arguably touches on every aspect of architecture. However, this paper is HBIM-focused, rather than BIM-focused, in order to contribute new knowledge in this area. According to Maxwell (2005), the conceptual background supporting a study such as this is typically based on a multidisciplinary review of previous literature, which supports the research domain and enriches the study's conceptual background. Based on this multidisciplinary perspective, the study will take the form of illustration through knowledge visualisation to simplify the process of HBIM and its related concepts and processes.

According to Tergan and Keller (2005), knowledge visualisation may help in reducing process complexity, facilitating knowledge transfer to others.

Evolution of BIM throughout the Building's Lifecycle

In the age before BIM, the traditional media of communication for various phases of a building's lifecycle were two-dimensional (2D) drawings. However, the introduction of CAD software has facilitated the use of 3D graphical models among all architectural design phases. In addition, recent years have witnessed a consistent challenge for providing a conventional 3D model with the fourth, fifth, and even sixth and seventh dimensions (see Figure 1). Koo and Fischer (2000) showed the utility of 4D models for virtual construction and space-conflict identification. This model is basically a 3D model linked to the time schedule that allows considerable saving of resources prior to construction and avoiding re-work during the project (Heesom and Mahdjoubi, 2004). Other studies refer to 5D models that integrate a 3D drawing with time and cost estimates, and enable value engineering for owners, project engineers, and managers (Bryde et al., 2013; Goedert and Meadati, 2008; Tanyer and Aouad 2005). Furthermore, the definition of BIM as modelling of the graphical and non-graphical aspects of the entire building's lifecycle in a sustainable system reveals the utility of 6D models, which underlines the strict relation between object modelling and information regarding different aspects. All these models support the maintenance process, which represents the 7D model (Bryde et al., 2013; Mohandes et al., 2014; Oreni et al., 2013).

According to recent terminology, these multidimensional models are now described as BIM, which differentiates itself as an object-intelligent architectural CAD tool rather than a drafting one (Murphy et al., 2013; Thomsen et al., 2010). Consequently, BIM could be the key approach to adopting the integration and shifting to a more integrated database paradigm in a post-BIM age. New digital information systems allow for the production of nD models that can be used for more operations, especially when dealing with historic heritage (Dore and Murphy, 2012). This infinite ability is based on the concept of further applications of high-capacity information that can be stored in a 3D intellectual building model, including construction details, specifications, cost, warranties, systems, construction sequences, off-site fabrication schedules, and shop drawings (Arayici, 2008; Arayici and Hamilton, 2005; Thomsen et al., 2010).

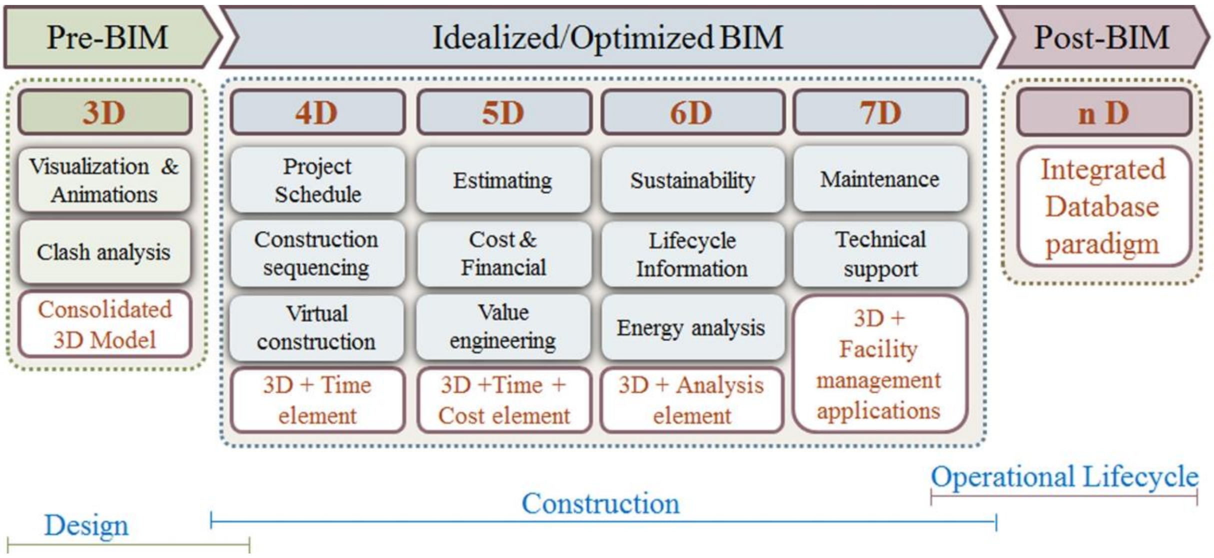

Figure 1. BIM nD terminology through the building's lifecycle.

Based on these models illustrated in Figure 1, BIM can bridge the information loss associated with handling a project from design team, to the construction team and to the building owner/operator, by allowing each stakeholder to add to and refer back to all information they acquired during their period of contribution to the BIM model. To ensure efficient management of information processes throughout this span, a BIM manager can help support multidisciplinary BIM to drive analysis, project schedules, estimating, sustainability and maintenance. This would help minimise problems for the resolution of all potential issues and interferences prior to the start of construction. In addition, this can yield benefits to the facility owner or operator through the building's lifecycle.

BIM Origins and Historic Preservation

The concepts, approaches, and methodologies that are now identified as BIM date back to the early stages of CAD in the 1980s, while BIM terminology has been in circulation for at least 15 years (Eastman et al., 2011). While BIM had originally been intended for new architecture, modern BIM software is being adopted for cultural heritage preservation and management of historic buildings (Fai and Rafeiro, 2014; Garagnani and Manferdini, 2013). Thus, 3D cultural heritage models have become a topic of great interest in recent years. One reason for this is more widespread use of surveying techniques for recording cultural heritage sites. These technologies have made it possible to remotely record complex structures in an efficient and accurate manner, which would not have been possible by the older surveying methods (Dore and Murphy, 2012).

FROM TRADITIONAL REPRESENTATION TO HBIM

Communities seek to preserve their heritage because their historical resources are their only physical link to the past. However, heritage buildings are subject to erosion and deformation; because they last a long time, they go through many phases of damage and repair. As a result, preserving such buildings is an important, complex, and diverse concept that brings together a wide domain of information. Resources linked to this heritage may be physical or nonphysical. Moreover, all these resources are listed and described by a variety of metadata specifications (Allen et al., 2003; Respaldiza et al., 2012). Thus, capturing and modelling 3D information regarding the built environment is a big challenge. Due to the complexity of these sites, building 3D models through traditional representation is time-consuming and difficult, usually involving a lot of manual effort (Allen et al., 2003; Arayici and Hamilton, 2005). Thus, it is important to maintain an accurate record of these buildings using 3D model-building technology. A number of modelling techniques and technologies are now used for this purpose.

High-definition Surveying Methodologies

In the case of heritage-building documentation, the first step is to collect data by storing topological information and content relationships to several devices from paper sheets to analytical software engines (Garagnani and Manferdini, 2013). In the last few years, surveying techniques have gained attention, especially in the context of built heritage, as summarized in Table 1, which illustrates 3D data acquisition by surveying and by using well-structured 3D modelling techniques, including the image-based method, the range-based method, and a combination of the two. In addition, many works have been published with regard to the comparison and the integration of the image-based and range-based methods. Most of this research works focus on their application to historical documentation. The methodology used for such literature usually involves recent and contemporary devices that offer a high level of accuracy and reliability while capturing the details of an architectural form (Brumana et al., 2013). However, for generation of a complete, accurate, and detailed model, semi-automated methods with manual measurements are still preferred (Stefano, 2015).

Table 1: Review of high-definition surveying methodologies. Adapted from (Arayici, 2008; Arayici and Hamilton, 2005; Baik et al., 2013; Guarnieri et al., 2006; Noh et al., 2009; Oreni et al., 2013).

Technique		Description	Advantages	Disadvantages
Image-based methods	Image-based modelling	• Using images for the reconstruction of 3D models by photogrammetric survey. • Using mathematical models to pick up 3D object information from 2D images or recover 3D data by shape from shading, texture, and contour.	• Widely used for geometric surfaces, precise terrain, and city modelling. • Provides both geometry and surface texture. • High geometric accuracy without capturing all the finer geometric details.	• Lack of details when compared with laser scanners technology.
	Image-based rendering	• Using images as modelling and rendering primitives when limited visualization is required. • Relying on accurate camera positions or performing automatic stereo matching.	• Good for the generation of virtual views. • More realistic and faster renderings to simplify the modelling task.	• Does not include the generation of geometric 3D models, but it might be considered.
Non-image based methods	Range-based modelling	• More recent and familiar method of 3D data acquisition by using laser scanners technology. • It can be airborne or terrestrial. However, the scanning principles and output from the scanning, which is point cloud data, are the same. • It is required to make multiple scans from different locations, which adjust to object size, shape, and occlusions.	• Rapid and active technique to acquire point clouds describing all the 3D building's information down to millimetre detail. • The resulting model can be sliced through different planes to produce accurate plans and elevations. • Suitable for both expert and non-expert users.	• Reliability and accuracy affected by weather conditions, the object itself, and the experience of the operator. • Output needs post-processing for good recording quality. • Costly active sensor. • Difficulty in extracting the edges.
Combination of image- and range-based methods		• This combination overcomes the disadvantage of the previous methods because no single technique can efficiently provide the complete model. Thus, the rational solution is determined by image-based methods and gets details by laser scanning.	• Allowing the generation of complete and detailed 3D models efficiently and quickly.	• More technical barriers and difficulties in extracting data during HBIM process.

HBIM Modelling Process

Modelling process denotes the creation of HBIM objects that represent all building information. This process involves a reverse-engineering solution, whereby complete engineering drawings can be extracted from survey data (Dore and Murphy, 2012; Cheng and Jin, 2006). This process is divided into three steps (see Figure 2).

- Data collection. The first step for the HBIM model begins with the survey of historic buildings to capture data using both high-definition surveying methods and traditional ones.
- Data processing. The next step involves the design and construction of a parametric library of objects, based on the manuscripts ranging from Vitruvius to 18th-century architectural pattern books. The data collected from each surveying method are processed independently (Baik et al., 2014; Guarnieri et al., 2006; Murphy et al., 2013).

Such models are then properly merged together, exploiting the editing capabilities to achieve a unique virtual representation of the historic building (Guarnieri et al., 2006).

- Data fusion. The final step of the HBIM process involves data fusion, in which the corresponding datasets using the BIM system define the historic objects as parametric components. In addition, the prototype libraries of parametric objects are mapped onto the point cloud and image survey data using a system of cross-software platform management. Thus, the final product is a set of complete 3D models, including detail behind the object's surface with regard to its methods of construction and material composition. In addition, the HBIM automatically produces complete engineering drawings and information for historic conservation and management; this includes 3D documentation, orthographic projections, sections, details, and schedules (Murphy et al., 2011, 2013; Rua and Gil, 2014).

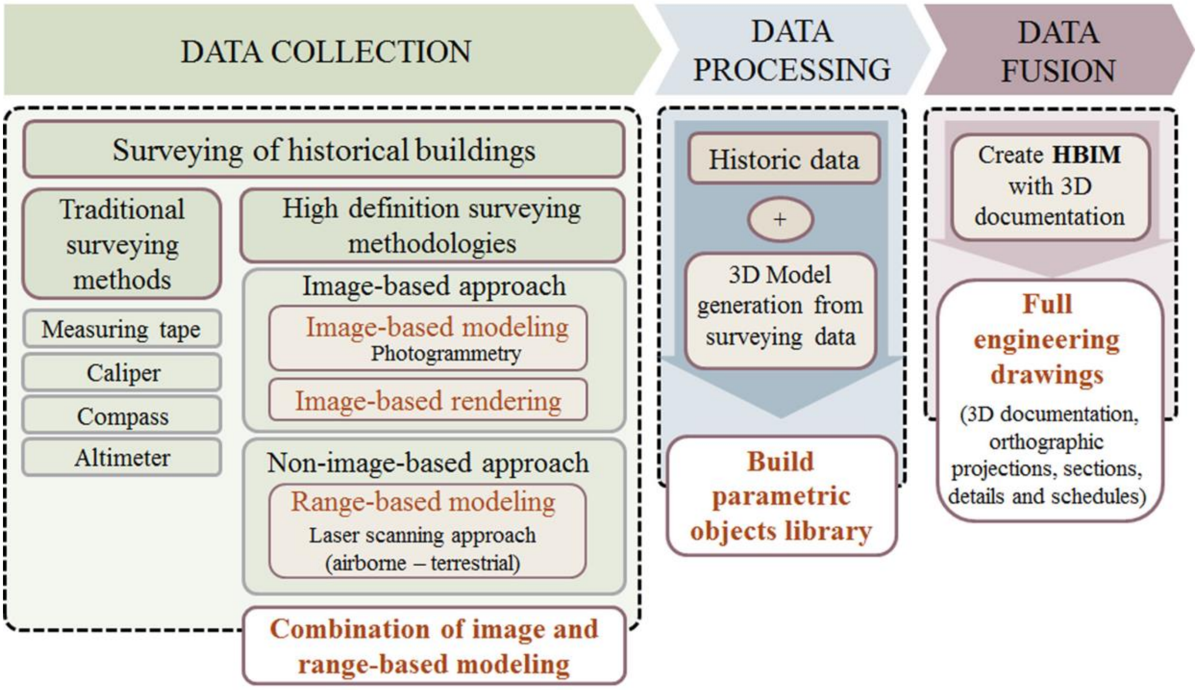

Figure 2. Systematic overview of surveying methodologies and HBIM process.

INTEGRATING PROCESS: ANTICIPATED FUTURE POTENTIAL OF HBIM

After creating and completing the process of HBIM, what is the final product? It is much more than a 3D modelling paradigm that supports other integrating processes in AEC.

These integrating processes cannot succeed without the help of Industry Foundation Class (IFC) data models that support collaboration between different stakeholders (Oogink, 2014; Zhang et al., 2015). The IFC data model has been in development since 1994 as a product data model for the full lifecycle record of buildings, by industry-led buildingSMART (formerly the International Alliance for Interoperability). The aim of IFC is to contribute to a sustainable building environment through smarter information-sharing and communication (Hetherington et al., 2011; Laakso and Kiviniemi, 2011).

In order to better understand these smart objects and processes, Bew et al. (2008) have introduced the BIM Maturity Diagram (see Figure 3). This model identifies with cover-related BIM technologies, processes, and policies through different levels (Succar et al., 2012), which are explained as follows:

- Level 0 BIM. Unmanaged CAD probably 2D, with paper as the most likely data exchange mechanism. This level not really BIM, but often a starting point for design and production information.
- Level 1 BIM. Managed CAD in 2 or 3D format using file-based collaborative tools, providing a common data environment, possibly with no integration. This level has been called lonely BIM.
- With Level 2 BIM there could be a number of different managed 3D BIM environment held in separate disciplines, utilising 4D programming tools and 5D cost elements.
- Level 3 BIM and beyond in which fully interoperable process and data integration enabled by IFC standards for data exchange. Managed by a collaborative model server, iBIM. This would be enhanced by the use of standard libraries of common objects that contain manufacturers' data (Bew et al., 2008; Sec Group Guidance on BIM, 2012).

In the BIM Maturity Diagram, the purpose of using HBIM is to provide an interactive solution to move from the zero level of BIM to more advanced levels like Levels 2 and 3. Moving up through the levels of this technology leads to seamless working and effective data and process management. However, a majority of the market is still working with Level 1 processes, and the best in class are experiencing significant benefits in Level 2 (Baik et al., 2014; Oreni et al., 2014; Porwal and Hewage, 2013). Thus, in the near future, HBIM may be located at Level 3. The shaded area in Figure 3 identifies the buildingSMART open platform that supports constructing and sharing historic libraries.

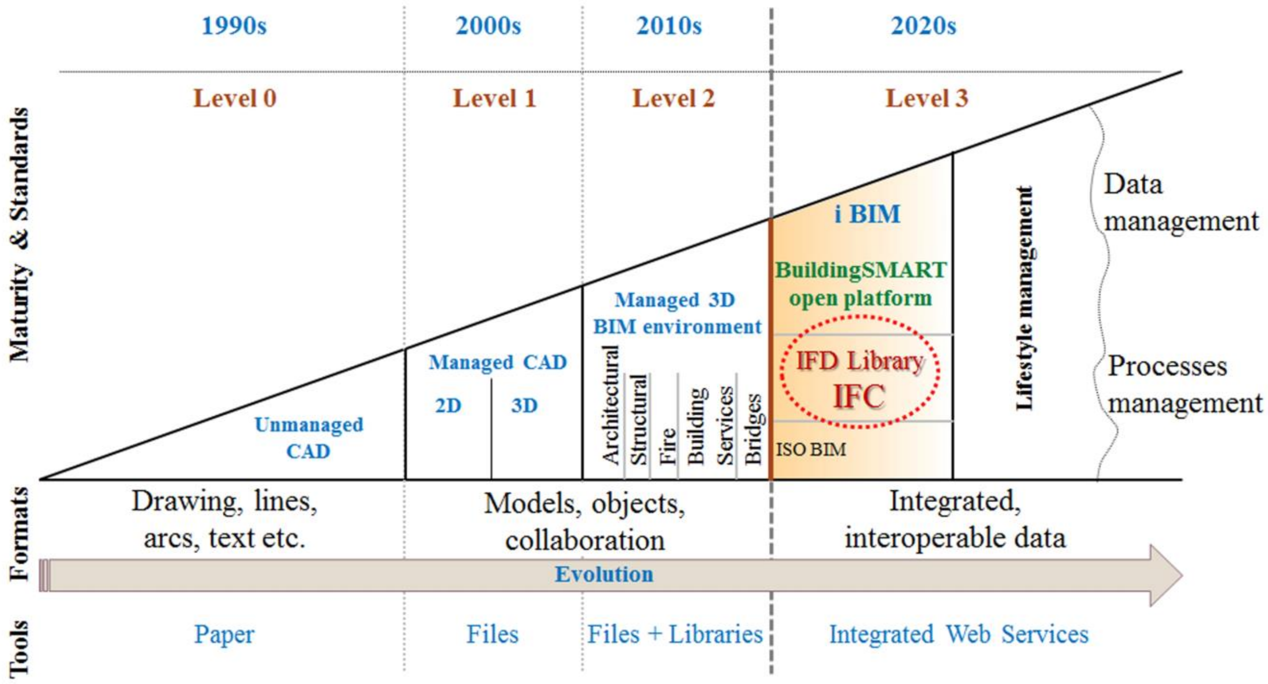

Figure 3. BIM maturity diagram. Redrawn after (Bew et al., 2008; Porwal and Hewage, 2013).

Towards Standardization

This point reviews the global perspective on HBIM - i.e. the international implications for shared and open libraries. Therefore, an information protocol is required to access BIM data. To achieve this aim, the buildingSMART open platform has developed a common data schema that makes it possible to hold and exchange data between different software applications. In this context, the ISO-registered IFC is the main buildingSMART data model standard and it is in the process of becoming an official international standard. While this open platform struggles to standardize BIM within the AEC industry, an even greater challenge may be to standardize BIM procedures for modelling historic buildings, where elements differ in scale from instance to instance and where the BIM model directly corresponds to the documentation strategy employed. Guidelines for the standardization of BIM procedures are currently governed on national levels across the world; however, there have been international collaborative efforts to develop stronger frameworks within a common exchange format (Arayici, 2008; Fai and Rafeiro, 2014; Oreni, 2013). However, the literature review indicates that the IFC model is complex, reflects the semantic richness of building systems, and offers different ways to define architectural digital elements, together with their features and behaviours (Eastman et al, 2011; Hetherington et al., 2011; Li et al., 2008; Venugopal et al., 2010). At present, IFC is the most supported protocol among the major BIM software vendors that supports complete interoperability (Porwal and Hewage, 2013).

Towards Interoperability

Another dimension of the generated HBIM model concerns its interoperability. The different factors involved in the conservation process can import information from the HBIM due to the interoperability of exchange formats. Interoperability in the AEC field has traditionally relied on file-based exchange formats and is characterized by the seamless sending and receiving of building data into multiple applications (Hetherington et al., 2011; Neuhold, 2014). Although BIM may be considered an independent concept, the associated management benefits of BIM are practically dependent on the shared utilization and value addition of integrated model data (Arayici, 2008; Oreni et al., 2014). The issue of interoperability has been widely and largely addressed by many researchers. In additions, international organizations have developed various practical details (Jung and Joo, 2011; Taylor and Bernstein, 2009).

Towards Integration and Collaboration

Within the framework of this study, BIM also supports the concept of Integrated Project Delivery (IPD), a novel project delivery approach that allows model-based collaboration between people, systems, and business structures and practices. This level of integration and collaboration not only improves efficiency and reduces errors, but also enables exploration of alternative approaches to reduce waste and optimize efficiency through all phases of the building lifecycle (Porwal and Hewage, 2013).

As the model is created, team members constantly refine and adjust their sections according to project specifications and design changes to ensure that the model is as accurate as possible before the project physically breaks ground (Azhar, 2011; Bryde et al., 2013). In this way, HBIM becomes a collaborative strategy in architectural design, in which the term information implies a sense of transparency among team members in order to generate a team working culture devoted to efficiency and integration, and not merely focus on software mastering (Garagnani and Manferdini, 2013). Although several professional organizations support the advancement of IPD and several projects have demonstrated its benefits, the number of projects using IPD remains relatively small (Kent and Becerik-Gerber, 2010).

Towards Automation

As discussed earlier, advances in engineering provide access to the latest knowledge to support the automation process in architectural heritage. Recently, high-definition surveying techniques have been rapidly advancing with part of the focus on developing new technologies for applications on architectural heritage documentation. Automation of the data acquisition process has also helped to develop models that represent reality. According to the technology used, these are efficient processes that are widely applicable to determine the state of repair of heritage buildings. These advances have allowed semi-automated and automated solutions, available commercially, and web-based software, to be used to obtain 3D point clouds and textured mesh surfaces. Full automation of the HBIM process of image orientation and matching can facilitate and speed up the data processing task that, in some cases, could be a never-ending process if performed manually (Baik et al., 2014; Rua and Gil, 2014). However, these automated methods are still under investigation in the research community; therefore, it is preferable to check results by manual measurements even though this is time-consuming (Guarnieri et al., 2006; Stefano, 2015).

Towards a Shared Library

To create automated documentation, it is necessary to integrate parametric models with an interactive library. Parametric models are related to data collected in a database; every change of a parameter causes a change in the shape of the elements. A shared library for historical elements does not exist at the moment; however, efforts are being made by the international community to build a shared library with common vocabularies. In this context, the international framework for dictionaries (IFD) is a mechanism that allows the creation of multilingual dictionaries in several research fields. The dictionary, named IFD Library, is a reference library intended to support improved interoperability in AEC. This library provides a flexible method to link existing databases with construction information to a buildingSMART platform. Given that the IFD defined inside the BIM software are not exhaustive for the historical building domain, the inclusion of dictionaries inside the historical building framework (H-IFD) aims to create an open archive that is updatable and dynamically adaptive to the real context of the historic buildings. Once progressively defined, HBIM object libraries—i.e. informative systems developed to support planned conservation activities—could be implemented and integrated with the H-IFD libraries in order to share common vocabularies (Brumana et al., 2013; Oreni, 2013).

Towards Documentation

Detailed documentation of architectural heritage, the last and most important point, is the ultimate aim of the HBIM process. HBIM is the dynamic database of a historic building with an improved coordination of construction documents, in which geometry, spatial relationships, geographic information, and other quantities or properties of building components are structured and documented (Volk et al., 2014). The advantage of implementing BIM models in heritage architecture is the possibility of establishing digital documentation involving different types of information in the same building database (Fai et al., 2011). This documentation should be based on a common vocabulary, taking into account the characteristics of the building and on data gathered through a systematic and unified process. The aim of this process is to describe models in detail according to the specific situations. The individuation of shape grammar and stylistic rules can be used to build a library of the historical elements of heritage architecture (Brumana et al., 2013; Oreni, 2013; Stefano, 2015).

In light of these integrating industry processes, it seems that the technology to implement BIM is readily available and rapidly maturing; active proponents claim that BIM can be used for several purposes. The ability to make use of commonly shared and flexible information constructed by these towards processes would certainly support the development and application of knowledge to various situations of historic preservation and management. However, they still require more practical investigation in order to achieve ideal standardization, smart interoperability, and integration.

Challenges and Barriers to HBIM Implementation

This study has been compiled to provide an impartial view to help architects understand recent digital documentation in the field of historic preservation and management. In this context, after reviewing HBIM-related technologies, applications, and potentials, it is obvious that BIM potential benefits are widely acknowledged and increasingly gaining popularity. However, this model currently faces a real challenge because of extreme difficulties in obtaining full documentation. In addition, critical aspects and barriers in the case of complex object modelling need to be further investigated. As a result, BIM adoption has been much slower than expected. This technology has not been widely applied primarily due to technical and legal reasons (Arayici, 2008; Brumana et al., 2013; Rua and Gil, 2014; Zalama et al., 2011).

The technical reasons can be broadly classified into the following (Azhar, 2011; Garagnani and Manferdini, 2013; Rua and Gil, 2014):

- The difficulties in entering survey data into a BIM system.
- The need to standardize all BIM processes and to define guidelines for its implementation.
- The need for well-defined transactional construction process models to eliminate data interoperability issues.
- The limitations of BIM systems in reproducing the state of conservation and deformations caused by time in building components, since they are mainly oriented for new buildings.
- The obstacles due to the use of different 3D modeling software—i.e. their cost, the interchange formats, the interoperability, and so on.

In addition to technical issues, another aspect worth mentioning is the legal risks; Azhar (2011) summarizes these risks as:

- Lack of clarity on the ownership of BIM data and the need to protect it through copyright laws and other legal channels. To prevent disagreement over copyright issues, the best solution is to set forth ownership rights and responsibilities in the contract documents.
- Responsibility for the accuracy and coordination of cost and data scheduling must be contractually addressed. Taking responsibility for updating BIM data and ensuring its accuracy involves a great deal of risks. One of the most effective ways to deal with these risks is to have collaborative, integrated project delivery contracts (Azhar, 2011).

All these reasons have created a distance between academic research on HBIM and practical applications. In order to be as faithful as possible to reality, these circumstances show that capturing and modelling of real-world information for built heritage are very challenging even though a number of techniques and technologies are now in use.

ROLE OF BIM IN ARCHITECTURAL HERITAGE: ESTABLISHING THE FRAMEWORK

Based on multidimensional models of the BIM paradigm, it is clear that there is probably no formal meaning of BIM available, but there are many proposals for definitions describing tools, processes, and technologies (Eastman et al, 2011; Jensen and Jóhannesson, 2013). This, in turn, helps the study to frame the HBIM paradigm with its own vision, especially in the absence of a holistic approach in existing literature, few theoretical articles in BIM relates to historic preservation and management are found.

In the field of management of historic preservation, the benefit from HBIM implementation is the possibility of connecting historic building information with integrated processes in the AEC industry. These integrated processes are strongly supported by technology tools and are continuously improved in order to reach higher quality, reliability, optimized scheduling, reductions in errors and costs, together with prevention of any possible project misinterpretation. Therefore, the HBIM paradigm has to be considered not only as a set of software to produce drafts and models, but also as a pipelined process among different stakeholders who share common information within definite policies (Eastman et al., 2011; Garagnani and Manferdini, 2013; Oogink, 2014; Stefano, 2015).

Building and construction processes have evolved significantly in the past few years. Recently, a lot of other specialists have been involved in these processes and related decision-making, including non-professionals (Mahdavi et al., 2014), especially when dealing with historic buildings. In this context, BIM and its integrated tools, processes, and technologies have been developed to meet the requirements of different stakeholders (Hetherington et al., 2011).

Kymmell (2008) indicates that engaging people during BIM implementation is vital and goes on to list three interrelated pillars for BIM implementation: people, technology, and process. BIM is about people and process as much as it is about technology (Sec Group Guidance on BIM, 2012). However, it is essential to define standards for both data content and format exchange among these pillars, in order to allow the different factors in the decision-making process to access information. In addition to these pillars, Succar (2009) indicates the importance of policy approaches, including common vocabulary of terms, metrics, and benchmarks that enable efficient communication (Kassem et al., 2015).

According to the mentioned pillars by Kymmell (2008), Mulenga and Han (2010), Sec Group Guidance on BIM (2012), and Succar (2009), the philosophy is built upon these pillars and they support the structure of the proposed framework. Based on this holistic vision, there is an indication that the framework of HBIM implementation has four interrelated pillars: people, technology, process, and policy. These pillars do not have fixed boundaries but are merged with each other, and each is integral to the performance of the others. Table 2 provides a brief introduction to each pillar embedded in the theoretical framework. In addition, the following points summarize the pillars' concept.

- The first pillar deals with people either specialists or not. Their roles differ from insert, extract, and update or modify information in the building model. Hence, in order to create HBIM culture that promotes creativity, learning and feedbacks through bottom-up approach makes people to being part of the decision-making process.
- The second pillar presents technology either hardware or software. There is a wide range of devices used on surveying and representation methods that offer a high level of accuracy and reliability while capturing the details of an architectural form. On the other component, due to the complexity of gathering all the relevant information when working with BIM some companies have developed software designed specifically to work in a BIM framework. These packages differ from architectural drafting tools by allowing the addition of further information (analysis, project schedule, estimating, sustainability and maintenance information, etc.) to the building model.
- The third pillar supports modelling and integrated processes. These processes gather and deliver information to support the development and application of knowledge to various situations in a harmonized manner under the guidance of the designated policy pillar.
- The fourth pillar deals with policy for further analysis, management, and control. Policy components must, therefore, be accurate to meet preservation objectives set by project stakeholders. Through embedding format, standards, codes, manuals, criteria, and recommendations information in BIM models. These policies emphasize the management process and can set, organize, develop, and monitored the whole HBIM implementation.

Table 2: Framework pillars and components. Adapted from (Bew and Underwood, 2010; Eastman et al., 2011; Hetherington et al., 2011; Kassem et al., 2015; Kiviniemi, 2012; Stefano, 2015; Succar, 2010; 2012; Thomsen et al., 2010; Utiome et al., 2014).

Pillar		Description/ Key Functions	Examples	Output
People	Specialist	• Management committee that must set policies to adopt the technology.	Designers, engineers, architects, contractors, facility manager, suppliers, fabricators, financing bodies, authorities, lawyers, occupants	**Historic preservation and management**
	Non-specialist	• Different stakeholders who use and benefit from technology.		
Technology	Hardware	• Devices used in recent surveying and representation methods.	Image-based methods Range-based methods	
	Software	• Required through buildingSMART open platform. • Allowing the addition of further information. • Supporting import/export processes.	BIM software (e.g., Bentley AECOsim Building Designer, ArchiCAD, Tekla Structures, MicroStation, Autodesk Revit, Synchro PRO, VectorWorks Architect)	
Process	Modelling	• Throughout gathering all the relevant building information.	HBIM (e.g., Data collection, Data processing, Data fusion)	
	Integrated	• The related process in AEC industry.	Standardization, integration, collaboration, documentation, automation, shared library, interoperability	
Policy	Mandates	• Prescriptive and dictated by an authority.	Format Standards Codes Manuals Criteria Recommendations (e.g., IFC, IFD, H-IFD, IPD)	
	Protocols	• Providing detailed steps to reach the goal.		
	Guides	• Descriptive and optional to clarify goals or simplify complex topics.		

DISCUSSIONS

HBIM has already been used in many heritage conservation projects around the world (Allen et al., 2003; Arayici, 2008; Baik et al., 2014; Brumana et al., 2013; Cheng and Jin, 2006; Dore and Murphy, 2012; Fai et al.,2011; Garagnani and Manferdini, 2013; Guarnieri et al., 2006; Li et al., 2008; Murphy et al., 2013; Noh et al., 2009; Oreni et al., 2014; Quattrini et al., 2015; Respaldiza et al., 2012; Rua and Gil, 2014; Zalama et al., 2011). These situations could allow further integrated documentation of both tangible and intangible heritage into a single parametric object that provides support to advanced programs for the long-term management of heritage architecture and guarantees sustainable involvement and maintenance over time (Fai et al., 2011; Oreni et al., 2013; Stefano, 2015).

HBIM automatically produces all architectural drawings, 3D models, 2D orthographic plans and sections, details, and schedules. These models are highly suitable for disseminating culture to enable society to view and interact with heritage files with the goal of continuous improvement (Baik et al., 2014; Rua and Gil, 2014; Garagnani and Manferdini, 2013). Thus, the use and implementation of HBIM extend beyond the stages of planning and design process to affect and influence every process involved through the building's lifecycle. HBIM has proven valuable benefits to society in this field. This tool enables all people involved during the HBIM implementation to share information contributing to the documentation of a historical building and to remain at the same location, thus allowing efficient management and preservation of the buildings. Therefore, HBIM can span multiple levels with many people, processes, and associated supporting technologies, each of which may require different internal data model representation. Thus, data exchange is a critical aspect and lies at the core of this technology.

In every level of BIM, the fact is that effectiveness is about people and process, not just the information technology. Both the people and the technology are essential for the proper functioning of the process. All levels of BIM will require changes to people and process alongside the adoption of new technology. This is particularly true especially in moving up towards Level 3 BIM and beyond (Sec Group Guidance on BIM, 2012). For fully HBIM implementation, there will need to be significant changes to the processes in order to exploit the technology to its maximum; and the people need to be on board.

Consequently, the aim of this review is to propose a theoretical framework which summarizes co-related information about the implementation of HBIM in historic preservation. This framework attempts to understand HBIM in a broader sense and to summarize the required information exchange in AEC. Other signs include providing basic knowledge for architects to begin thinking with this recent technology and assume their roles in using this smart platform. However, Jernigan (2007) indicated that integrating technology does not require that architects to throw away all of their proven tools and experiences but it require them to look at things differently and to separate the things that should be kept from those that should be replaced.

The proposed framework illustrates how people, technology, process, and policy interact to support historic buildings throughout their lifecycle, as depicted in the visualization of the theoretical framework (see Figure 4). This visualization try to simplify HBIM implementation and its related concepts and processes compared with pre-BIM age.

In the pre-BIM age, each of people, technology, process, and policy worked separately when dealing with information exchange that waste time, increase cost, and reduce management. On the other hand, Ayyaz et al. (2012) indicates that most organizations in post-BIM age are treating BIM as an add-on to traditional information methods of creating, storing, viewing and exchanging information. However, more efforts are still needed to educate people regarding culture change.

In post-BIM age, the framework is based on the four interrelated pillars of the HBIM paradigm: a) the people who use or interact with AEC in a collaborative environment; b) the technology used in recent surveying and representation methods or required in the buildingSMART open platform; c) the process associated with modelling and integrating models, and; d) the policy that organizes related exchange formats, protocols, and guides to deliver information. There is a need to look at these pillars where the buildingSMART information platform provides a central place to give all actors their own access to all building information. Most importantly, this platform bridges the boundaries between integrated processes associated with HBIM implementation by providing interactive interoperability to all actors in the decision-making process, which supports community efforts to safeguard heritage architecture.

The future of BIM is both exciting and challenging; the management job requires setting BIM standards, contracts, and regulations that are submitted to be entered into the model. At the same time, teams implementing BIM have to be very careful about legal issues, including data ownership, associated proprietary issues, and risk sharing. But most of all, it requires understanding how to organize this information from multiple sources into platform-based integration. Such issues must be addressed up front in the contract documents (Azhar, 2011; Bew and Underwood, 2010; Eastman et al., 2011; Thomsen et al., 2010). In this context, the implementation of HBIM still requires methodological discussion and practical experimentation in order to apply this kind of documentation in a broader heritage conservation and maintenance process. Some limits and barriers need to be investigated more extensively in the future with respect to the absence of freely available BIM assemblies and objects for heritage buildings (Brumana et al., 2013; Fai and Rafeiro, 2014). With these challenges in mind, HBIM libraries require wide and shared research on drawings, elaboration, and interpretation activities of data survey (Oreni, 2013; Stefano, 2015). In addition, standards and interoperable IFC and IFD for historic management need to be investigated and implemented. However, the continuous research, rapid development, and adoption in the field of BIM may overcome these challenges and other associated risks. In this respect, one can expect that the use of HBIM will continue to increase in the near future like other recent technology applications.

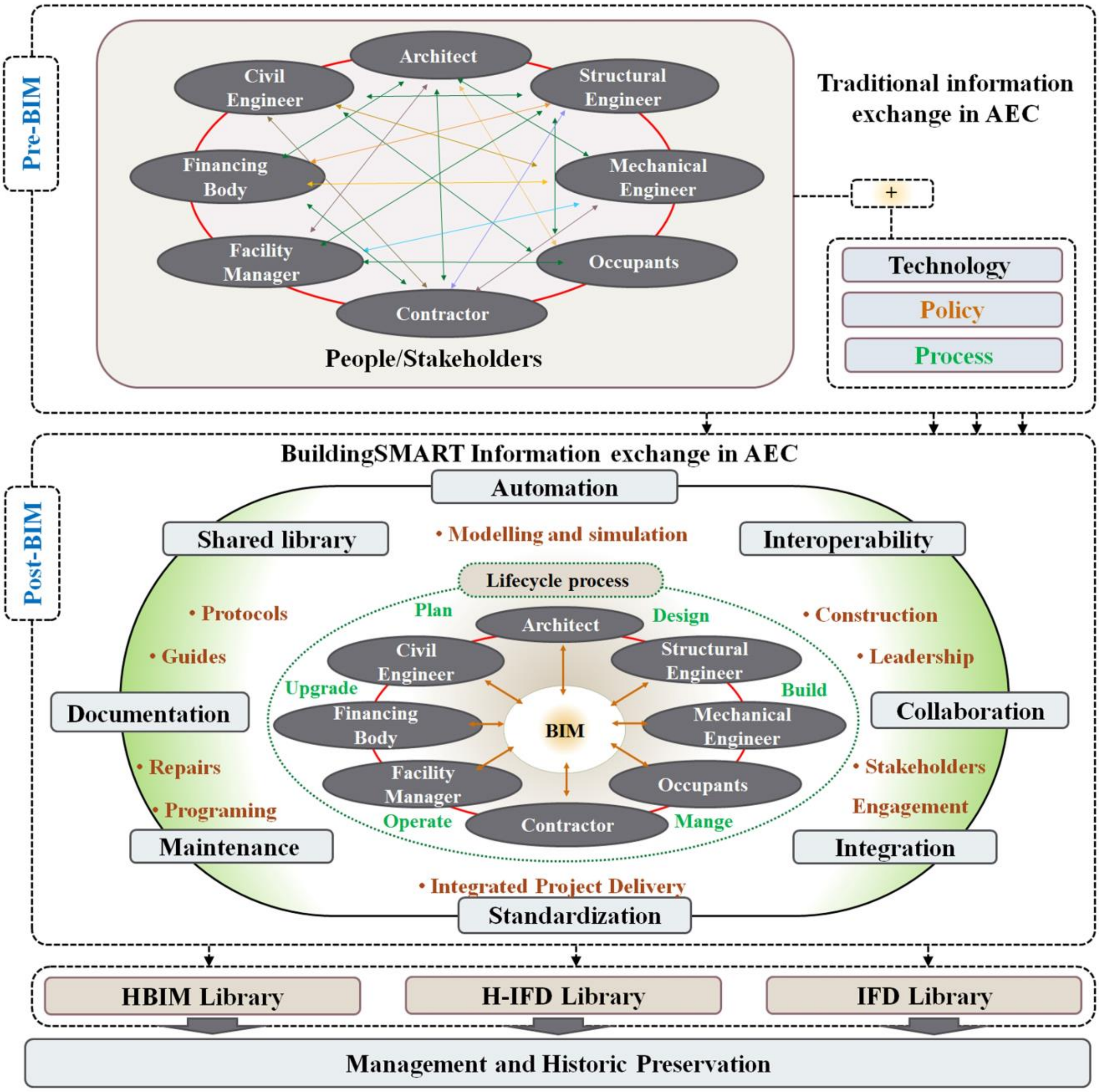

Figure 4. A visualization of the theoretical framework.

CONCLUSIONS AND FUTURE PERSPECTIVES

This paper reviewed BIM concepts, with a particular focus on its applicability and uptake within historic preservation in the AEC. In addition, an exploratory study was carried out to present 3D data acquisition. Although previous research investigations provide some insight into the BIM application to historical documentation, there is a need for continued research on the HBIM implementation.

This paper outlines the major challenges which face assembling a review in an interdisciplinary field of study. That is, constructing a review is a challenging process because there is often a need to draw on knowledge from a variety of fields. Another challenge relates to the absence of holistic and theoretical articles in BIM relates to historic preservation. In considering these issues, it is important to remember that this paper does not provide a conclusive implementation approach. The key contribution of this study is the proposal of a theoretical framework of HBIM, which bridges the knowledge gap by articulating issues regarding the technology of surveying methodologies with other informational, technical, and organizational issues of BIM. However, the proposed framework provides an initial background for developing more comprehensive study related to HBIM implementation in historic preservation and management.

As shown in this paper, HBIM database can, therefore, be used to gather information and make it available to researchers, professionals, and other parties involved in historic preservation. However, this model can represent a challenge with a high scope for further investigation into technical requirements and legal risks. What is required much thinking beyond 3D visualization to support other HBIM-related processes during information exchange in AEC.

In conclusion, it is hoped that this study is useful for architects and researchers in the field of heritage conservation and, therefore, contributes to a major shift in architectural thinking, while shedding light on the future of architecture and its relation to other scientific disciplines.

Finally, the presented study demonstrates the vision that focuses holistically on people, technology, processes, and policy to increase the impact of HBIM on society and support management of historic buildings. Therefore, a collaborative decision making is essential to a successful HBIM implementation. However, this entire potential is still far from being fully utilized in professional practice. It can be concluded that lack of knowledge about HBIM approach is the biggest issue in general. Thus, moving to HBIM is a much larger change, and thus requires both top-down and bottom-up approaches and the four pillars to be integrated simultaneously.

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THE DYNAMICS OF DAYLIGHTING AT A RESIDENTIAL COLLEGE BUILDING WITH THE INTERNAL COURTYARD ARRANGEMENT

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Abstract
Dayasari residential college building was designed with the internal courtyard that allows for numerous implementations of bioclimatic design strategies, especially on daylighting. The field measurement was conducted at eight unoccupied student rooms, selected as samples to represent ten scenarios and orientations that concerned with the level of radiation and penetration of sunlight. This study reveals the contribution of the internal courtyard in the residential college which allows the daylight penetration at the corridor areas and interior of the rooms through the transom over the entrance door, up to ten hours daily. Different amounts of daylight were measured in specific room scenarios to suggest on the most comfortable indoor living space. The recorded mean value for indoor varied from 37 to 286 lux, while in the corridor area 192 to 3,848 lux. However, the use of the large overhangs over the windows, wall openings in the room and trees with large canopy in the landscape setting should critically justify when the adequacy of daylight was drastically reduced in certain rooms.

Keywords: *Bioclimatic design, Illuminance, Internal courtyard, Residential college building*

INTRODUCTION

Daylighting is a technique that brings natural daylight into a building, through openings so that the day's natural light provides effective internal lighting (Fontoynont et al., 2004). Daylight is the total light from the sky dome which is affected by attenuation, due to the absorption and scattering in the atmosphere and it consists of direct (or beam), diffused and ground-reflected components (Zain-Ahmed et al., 2002a). The daylighting was introduced in building designs before the second half of the twentieth century when most of the buildings during that time have more windows than walls, high ceilings with high windows, also E-, U-, O- and H-shaped floor plans in providing daylighting (Lechner, 2009). In equatorial regions where the climate is hot and humid, most of the traditional buildings are constructed with wide awning or verandas shading the large windows which can be opened during most of the year, or specifically throughout the day and night for ventilation (Edmonds and Greenup, 2002).

The daylighting studies involve a great number of cross-disciplined design factors intertwined between the site planning, architecture, interior design, lighting design, electrical engineering and mechanical engineering (Phelan, 2002). All these factors have to integrate with occupants' characteristics, owner's operating requirements, task lighting requirements and the daily and seasonal solar cycles. There are three major developments that contribute to interests on the aspect of daylighting in building designs namely; the impact of light on human health, the growing influence of green building rating schemes and progress at lower cost, along with reliable, integrated control technologies to provide the responsiveness needed for comfort and energy savings (Reinhart and Selkowitz, 2006; Franzetti et al., 2004).

The right application of daylighting in buildings can reduce electricity usage for room illumination by more than 50% (Lechner, 2009; Ihm et al., 2009), while Zain-Ahmed et al. (2002b) proved that the adaptation of daylighting as passive solar design strategy in tropical buildings can help to conserve up to 10% of the energy used. By using computer simulation approaches, Li et al. (2005) have found that the application of daylighting can reduce the maximum cooling plant load and building electrical demand for the base case model by 5 and 9.3%, respectively. Lowering the usage of electric lighting in buildings, it can reduce the energy demand for cooling requirements resulted from the internal load from the artificial light (Leslie, 2003). The incandescent lamps introduce about six times more heat than daylighting and fluorescent lamps introduce about two times more heat than daylighting (Lechner, 2009). The electricity from an incandescent lamp heats up a wire filament causing it to glow and emit the light, where 90% of the energy produced is heat, not light (Mahlia et al., 2005). According to Leslie (2003), capturing day light in the buildings is capable to;

- improve the human performance and well-being through daylighting's impact on their aesthetics, vision, and photobiology, where experimental work indicates that the suppression of melatonin, the hormone responsible for regulating the body's internal clock or circadian rhythm is influenced by the exposure to light levels typical of daylight.
- possibly improve productivity, increase job satisfaction or reduce absenteeism.
- create interesting lighting effects that modulate throughout the day and year, while also providing a broad electromagnetic spectrum with excellent colour rendering.
- allow buildings to be lit at higher levels than those with electric lighting alone. This will allow people to continue working on certain given tasks during power shortages or breakdown.

The effectiveness of daylighting depends on several factors, including the building architectural features (shape, window area, glazing type), the building locations (Ihm et al., 2009), the surrounding climate and the requirements of lighting for specific purposes (Kischkoweit-Lopin, 2002). In the window design, it can include the size, location, orientation, external condition and the use of light diffusers which directly control the light level, daylight qualities and internal luminance (Jughans, 2008). Thus, improving the visual comfort while reducing the heat gain caused by light penetration (Yeang, 2008), can be conclusive in four daylighting strategies, as mentioned by Omer (2008),

- Penetration : collection of natural light inside the building,
- Distribution : homogeneous spreading of light into the space focusing,
- Protect : reducing, by external shading devices, the sun ray penetration into the building,
- Control : control light penetration using movable screens to avoid discomfort.

For multi-storey buildings, the most appropriate zones for active human activities should be located within the daylight zone, typically about 5m deep from the window wall or the top floor of a building with skylight (Leslie, 2003). Additionally, the critically visual tasks need to be placed near the building parameter, and light colour interior surfaces should be used towards reducing the luminance contrast between the windows and surrounding surfaces while increasing the visual comfort.

Therefore, the opening size of a window is the most important aspect that affects the penetration of daylighting in the building. The solar gains as the window to wall ratio (WWR) increase while the peak gains occur in the southwest-facing windows (Zain-Ahmed et al., 2002a). The optimum window opening for daylighting in Malaysia is 25% WWR, where the illuminance levels in a room do not reach 500 lux before 8.30 a.m. and after 4.30 p.m. for distances less than 1.75m from the window (Ibrahim and Zain-Ahmed, 2006). Nevertheless, there is no guidance for the maximum size of the opening when other practical requirements such as sun control, security and privacy should also be considered (Aynsley, 1999).

The daylighting is not only an energy efficient technology but also an architectural discipline that improves the performance of the building and occupants. Daylighting stands in prominence as the major factor in occupants' perceptions and acceptance of spaces in buildings. Successful energy saving through daylighting can only be realised when the building and system design support broader occupants' needs for comfortable and healthy indoor environments (Reinhart and Selkowitz, 2006). Unfortunately, the effectiveness of implemented bioclimatic design strategies, particularly daylighting in a building is rarely assessed once they are handed over to their users. There is lack of studies performed at the residential college building especially in the tropical climate region, as compared to the office or commercial buildings in the temperate climate region. Even worse, the designers often design with dreams far away from realistic situations when they fail to understand the features of the local climatic zone and living style (Maheswaran & Zi, 2007). The buildings normally do not fit the ecological and cultural contexts and do not answer to programmatic, practical and functional needs (Al-Kodmany, 2014). Thus, this study aims to evaluate the penetration and distribution of daylight in a residential college building, with the purpose of justifying the effectiveness of the recent adoption of bioclimatic design strategies in influencing the daylight penetration and distribution in the building through field measurements. Indirectly, this indicates the adequacy of daylight in achieving comfortable space as a habitat indoor environment, as prescribed by international and local standards. The selected residential college is an old building located in Kuala Lumpur, which is designed with an internal courtyard and numerous adaptations of bioclimatic design strategies, particularly on daylighting.

RESEARCH METHODOLOGY

The research has been conducted at a multi-residential building, which provides accommodation for university students and which is commonly referred as 'residential college' or 'hostel' in Malaysia. Concerning safety issues which limit the accessibility to the residential block, the field measurement was done for a very short period of time at a selected location, as determined by the residential college administration. The research approach is shown in the following research structure in Figure 1.

The field measurement was conducted in eight unoccupied student rooms, which are regarded to be the most excellent rooms in representing ten scenarios concerned with the level of radiation and penetration of sunlight into the student rooms. There are five best scenarios, which were labelled as 'B', and five contrary scenarios which were described as the worst scenarios and labelled as 'W'. All the ten identified scenarios are based on climatic design theories according to the previous studies, particularly in the tropical region (Lechner, 2009; Jughans, 2008; Yeang, 2008; Ahmad, 2008; Hyde, 2000; Davis et al., 2006; Konya and Vandenberg, 2011; Aynsley, 2007; Monteiro and Alucci; 2009); they are extensively explained in Table 1. Initially, two from eight selected rooms had been chosen to represent two different scenarios. The findings from each selected room will give a general evaluation of daylight penetration and distribution based on the identified scenario (Jamaludin et al., 2012). Theoretically, the worse or better conditions were expected in the room with the combination of two or more scenarios.

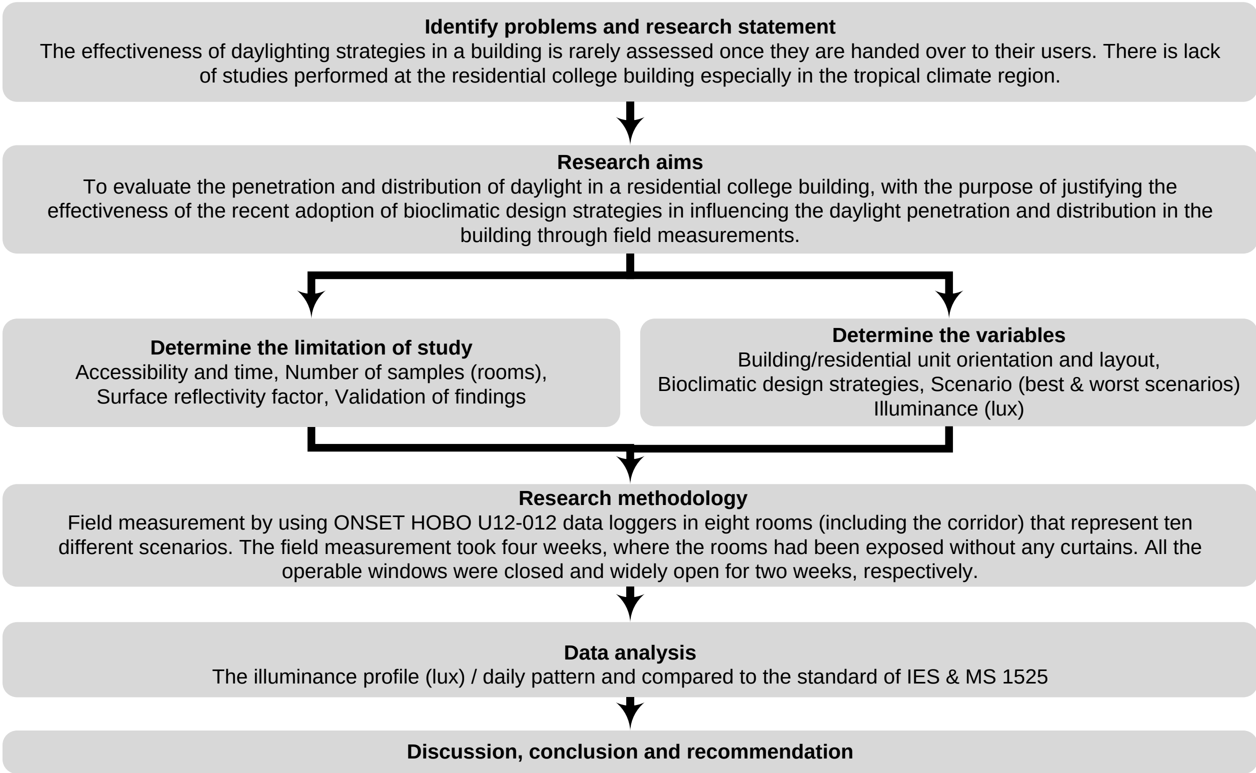


Figure 1. Research structure

Table 1: The 10 identified scenarios.

Scenario		Description
B1	North orientation	Receiving reflected heat radiation and penetration either from the west or east. Meanwhile, it is not influenced by direct heat radiation and penetration by man-made surface either on top or on the ground.
W1	East orientation	Receiving direct heat radiation and penetration from the east. Meanwhile, it is not affected by direct heat radiation and penetration of man-made surface either on top or on the ground.
B2	South orientation	Receiving reflected heat radiation and penetration either from the west or east. Meanwhile, it is not influenced with direct heat radiation and penetration by man-made surface either on top or the ground.
W2	West orientation	Receiving direct heat radiation and penetration from the west, while, not affected by direct heat radiation and penetration of man-made surface either on top or on the ground.
B3	Avoid direct contact with man-made surfaces on the top	Not receiving direct heat radiation and penetration from man-made surfaces on the top, i.e. roof, wall etc. and with north-south building orientation.
W3	Direct contact with man-made surfaces on the top	Receiving direct heat radiation and penetration from man-made surfaces on the top solely, i.e. roof, wall etc. and with north-south building orientation.
B4	Avoid direct contact with man-made surfaces on the ground	Not receiving direct heat radiation and penetration from man-made surfaces on the ground, i.e. tarmac, court etc. As well as, direct heat radiation and penetration neither from the east nor the west.
W4	Direct contact with man-made surfaces on the ground	Receiving direct heat radiation and penetration from man-made surfaces on the ground solely, i.e. tarmac, court etc., while not affected by directing heat radiation and penetration either from the east or west.
B5	Shaded	Shaded by landscape or trees or adjacent buildings and with north-south building orientation. Not affected somehow by direct heat radiation and penetration of man-made surface either from the top or on the ground.
W5	Exposed	Exposed to open spaces and with north-south building orientation. Not affected somehow by direct heat radiation and penetration man-made surface either from the top or ground.

For example, higher mean illuminance values in the exposed room with the west or east orientation imply that the room receives direct daylight penetration. On the other hand, lower mean illuminance values would be obtained in shaded rooms with the north or south orientation.

The study done by Chaiwiwatworakul and Chirarattananon (2013) on a double-pane window with enclosed horizontal slats for daylighting in buildings in the tropics was adapted to restructure the research methodological approaches on data collection. ONSET HOBO U12-012 data loggers for indoor measurements were fixed on both sides of the walls to find out the distribution level of daylight (lumens/ft^2 or lux) in the room (Hua et al., 2011). These data loggers were fixed on the room's core area for main activity; which is on the study desk at 1.10m above the floor (Kim and Kim, 2007; Jovanić at al., 2014). As adapted from a study done by Li and Lam (2003) on an investigation of daylighting performance and energy saving in a daylit corridor, ONSET HOBO U12-012 data logger was also fixed outside the selected rooms for the examination of the level of daylight outside the room, specifically in the corridor area. The location field measurement and all three data loggers are shown in Figure 2.

The measurement was done in four weeks, where the rooms had been exposed without any curtains. In the first two weeks, all the operable windows were closed, while in another two weeks all operable windows were widely opened. This is to find out the effects of facade design and building orientation in providing daylighting into the room in ten different scenarios, as the user's adjustment on the internal shading is subjective and unable to be generalised (Lim et al., 2012). The plastic net with 1.5cm^2 of mesh size with 0.5 to 0.6 of light transmittance has been fixed for the safety of data loggers during the opening of all operable windows. According to Ahmad (2008), Malaysia's climatic conditions are uniform throughout the year with only little seasonal variation and constant sunshine hours. In contrast, there are very distinguishable difference between the minimum and maximum daily temperature due to the day and night factor. Thus, the measurement was covered in a 24-hour period with one-hour interval between measurements (Dahlan et al., 2009). According to Li and Tsang (2005), data measurement is regarded as the most effective and accurate method of setting up reliable databases.

All the collected data were initially analysed by using the Hoboware pro software. In order to assess the level of daylighting in the building, the illuminance data were compared with the international and local illumination standards. The standards which are established by the Illuminating Engineering Society (IES) and Standards and Industrial Research Institute of Malaysia (SIRIM) with Malaysia Standard 1525 (MS 1525), were used in view of the most stringent standards (Department of Standards Malaysia, 2007; IES, 2011). The MS 1525 is the code of practice on energy efficiency and the use of renewable energy for non-residential buildings. Listed by the IES, the minimum of 100 lux is applied to circulation areas, corridor being one example. Meanwhile, 150 lux is for the living room in general, 400 lux for casual reading and 100 lux for the bedroom as referred to MS 1525. In addition, statistical computer software package was used for further statistical analyses that include a descriptive analysis, to find out the difference of the mean and maximum illuminance values between the indoor and outdoor.

BUILDING DESCRIPTION

The Dayasari Residential College (Dayasari RC) was established in 1966 with 18,212.51m^2 of the total floor area and leads other residential colleges in the University of Malaya campus in terms of its implementation of bioclimatic designs, especially when it comes to allowance for the best utilisation of daylighting (Jamaludin et al., 2012). This residential college is a low-rise and naturally-ventilated building and can accommodate up to 847 residents at one time. The building's orientation to sun path is north-south, which directly reduces the glare and thermal effect that can be collected inside the rooms. Only service areas such as toilets, bathrooms, stores, staircases and balconies are located at a west-east orientation.

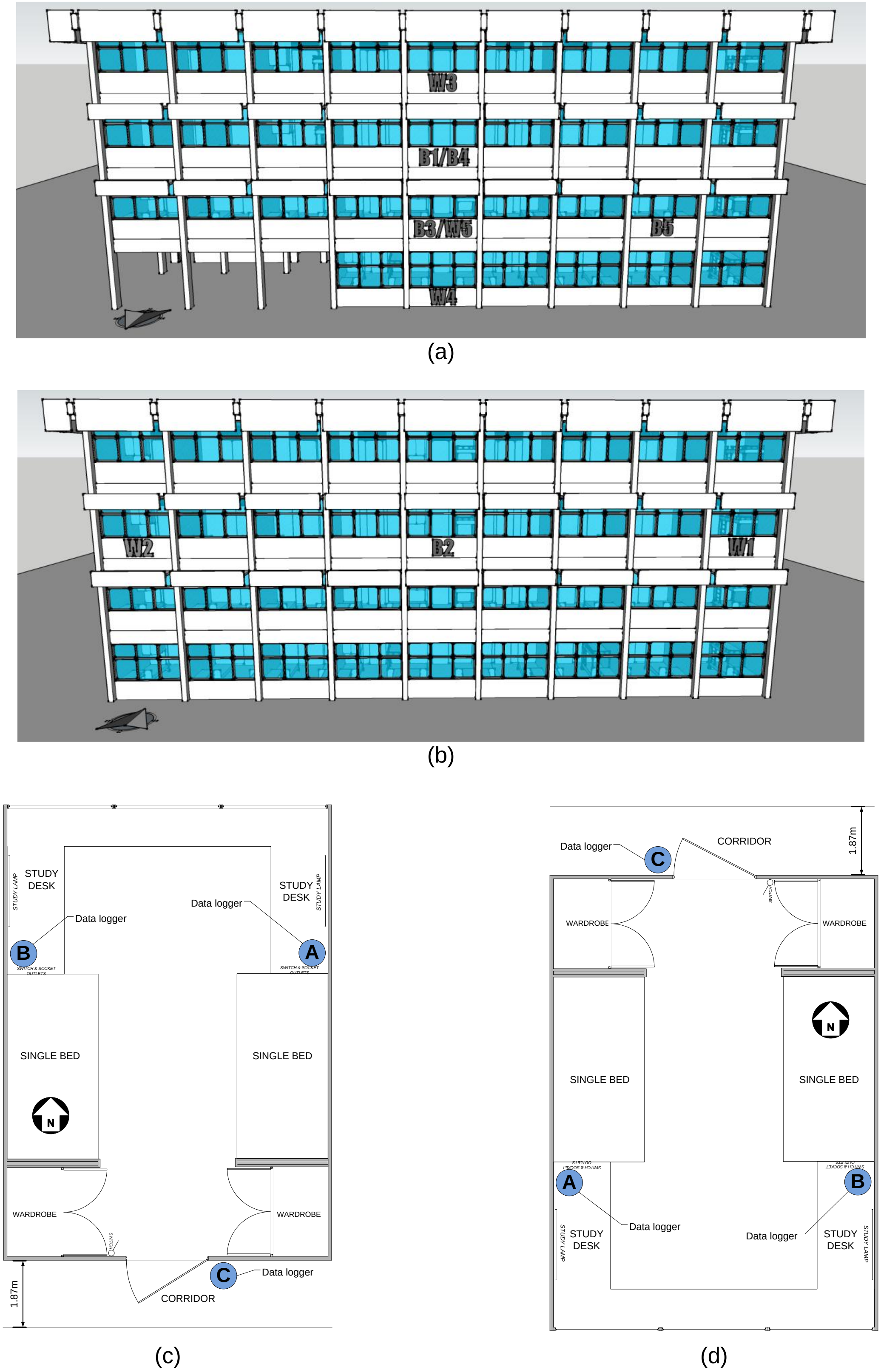


Figure 2. (a) (b) Location of field measurement, (c) Location of three data loggers for scenarios B1, B3, B4, B5, W3, W4 and W5, (d) Location of three data loggers for scenarios B2, W1 and W2.

The building layout is based on a courtyard arrangement that allows for the transom on top of the entrance door and wall to fully function, in providing daylight in the room, at least in theory. The typical room's floor area and volume are 16.35m^2 and 45.78m^3, respectively. With the open staircase area and a corridor that face the internal courtyard, the lamps do not need to be switched on during daytime as compared to other buildings with a linear arrangement of building layout (Jamaludin et al., 2011). As a consequence, Dayasari RC has to contain amongst the lowest Energy Efficiency Index (34.52 kWh/m^2/year) compared to the other residential colleges which are in the range of 40 to 125 kWh/m^2/year (Jamaludin et al., 2013). Based on the energy audit done by Jamaludin et al. (2013), the uses of electrical lamps at the Dayasari RC depend on the location and purpose. Generally, it is 12 hours in the corridor and in the toilets (from 7 p.m. to 7 a.m.), 6 hours in the room (from 6 p.m. to 12 a.m.) and 4 hours for study lamp (from 8 p.m. to 12 a.m.) daily. The typical elevation and floor plan of Dayasari RC are presented in Figure 3.

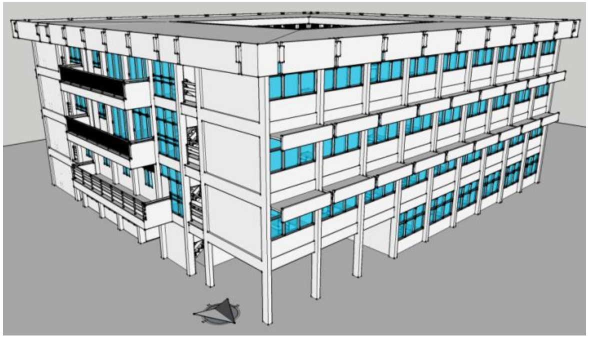
In light of the enclosure and facade design, Dayasari RC was designed with two special features; glare protection and adjustable/fixed opening options. There are two types of single glazed windows; namely the centre pivot and awning, which are a standard float and tinted glass with 0.56-0.60 of the visible transmittance. The Window to Wall Ratio (WWR) is fairly big, 0.66, while the window area is 6.41m^2. Subsequently, the operable window area is only 4.20m^2 with 0.43 of operable WWR. To date, the WWR is not efficient, as the ASHRAE 90.1 Standards Committee voted the current 0.24<WWR<0.40 for low-rise buildings (US Glass News Network, 2012). The WWR is the ratio of vertical fenestration area to gross exterior wall area and higher ratio can result in excessive daylight into the building (Yeang, 2008). The measured ratio of window to floor area is 39%, which is more than the prescribed rule of thumb for daylight design in Architecture's Data used by Neufert and Neufert (2012). The WWR in the range of 10 to 12.5% is recommended, while 10 to 25% was suggested by Gutherie (2010). There are large concrete overhangs along the window in each room; excluding the ground floor, in giving a significant shadow effect to the rooms. These overhangs are painted with white coated on the bottom surface and uncoated on the upper surface with 0.85-0.95 of the solar reflectance. The combination of the internal courtyard, transom on top of the entrance door and two types of single glazed window create cross-flow / two sided ventilation that encourages air circulation in the room. The implementation of bioclimatic design strategies at Dayasari RC are visualised in Figure 4.

Finally, there are about 61:39 ratio of soft and hard landscape areas with 0.607 of Biotope Area Factor (BAF); the proportion of green space to the entire development area. The Dayasari RC is surrounded by a highly diverse vegetated area as it is next to the foothill of Rimba Ilmu, the university's tropical botanical garden. Most trees are well matured with their canopies covering the ground that provides wonderful shading effects to the residential building (Jamaludin et al., 2011).

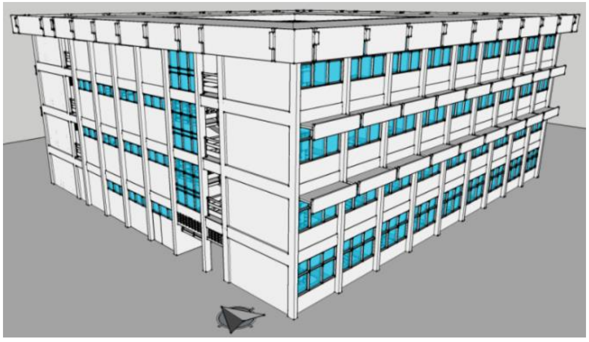
RESULTS

The illuminance profile of all eight rooms that represents ten different scenarios, in order to evaluate the penetration and distribution of daylight at a residential college building with the internal courtyard arrangement, is drawn in Figure 5. The profile shows in the form of daily pattern and compares the minimum requirements of the IES and MS 1525. The mean and maximum illuminance values (lux) for each room and corridor are presented in Table 2.

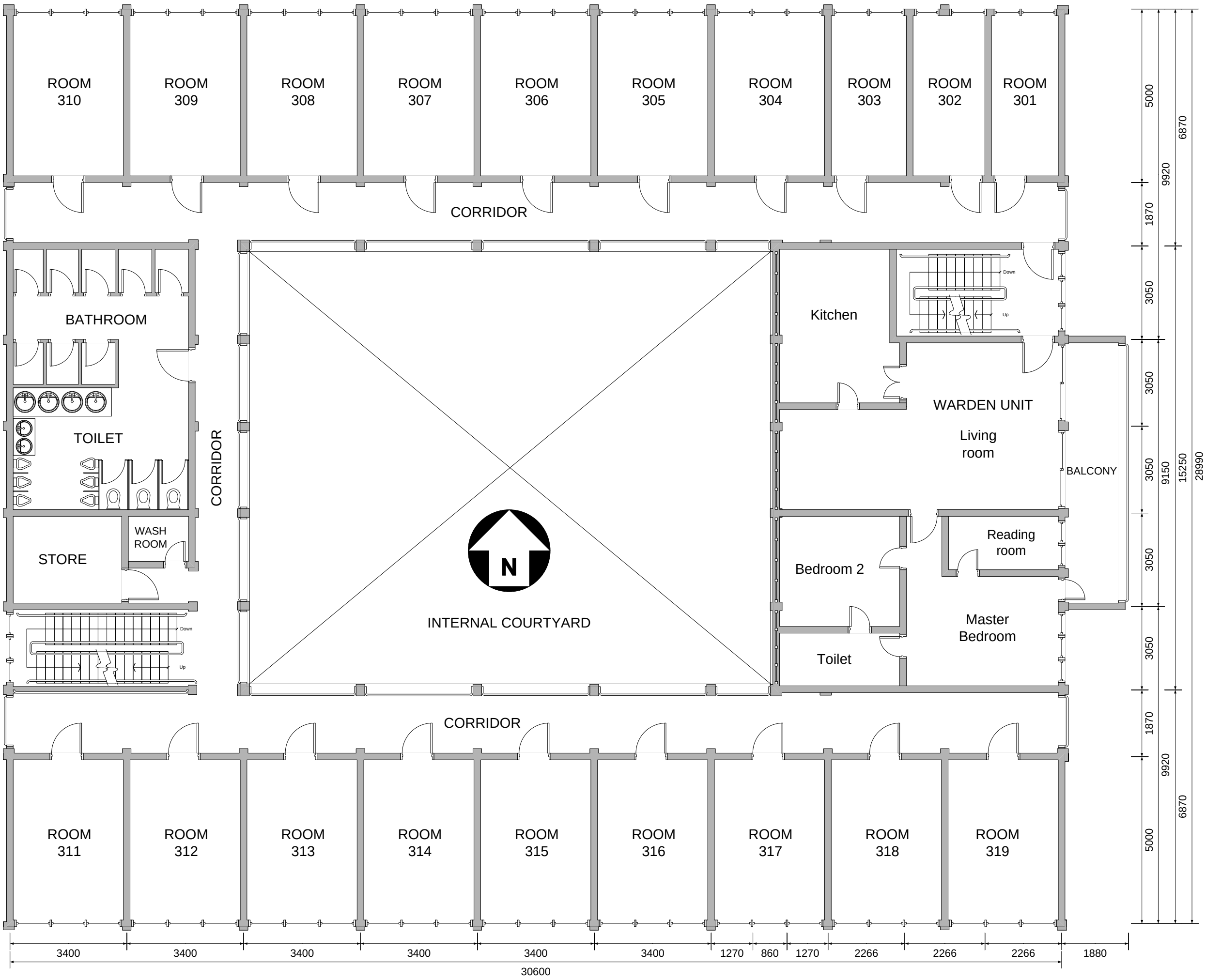
The adequacies of daylight in all selected rooms as presented in Figure 5, fulfil the minimum requirement of the IES for corridor (100 lux), along with MS 1525 for the living room (150 lux) and bedroom (100 lux). The availability of daylight was varied from 8 a.m. to 7 p.m. with regard to the scenarios represented.



Front isometric elevation



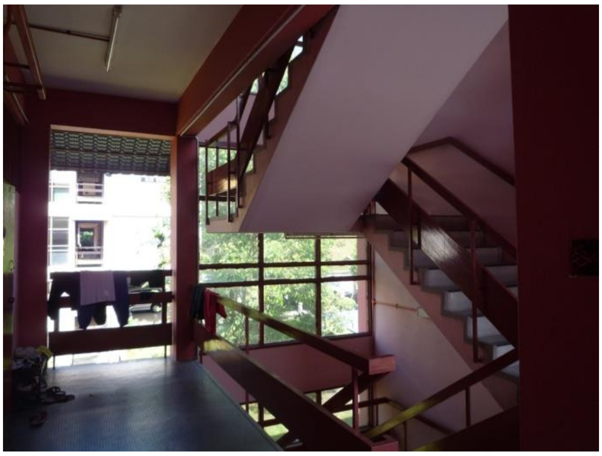
Rear isometric elevation



Floor plan

Figure 3. Typical elevation and floor plan of the Dayasari RC building.


(a)


(d)


(b)


(e)


(c)


(f)

Figure 4. Implementation of bioclimatic design strategies at Dayasari RC, (a) Internal courtyard in the middle of residential building, (b) Transom/fixed opening over the doorway of the room, (c) The wall opening in the room - creates a wind pressure, (d) Open staircase area, (e) two types of single glazed window with standard float and tinted glass, centre pivot and awning, (f) Glare protection and adjustable natural ventilation options.

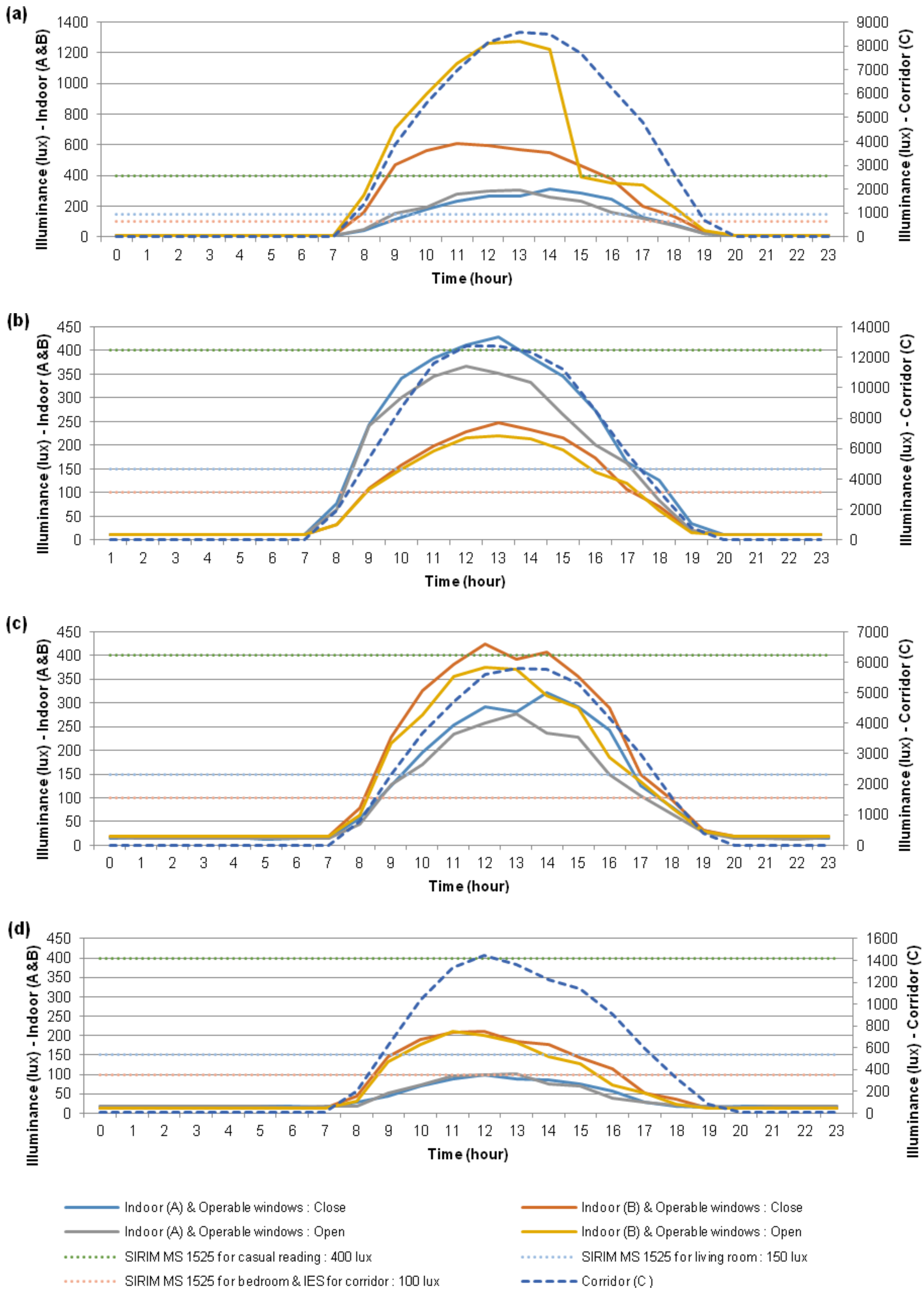


Figure 5. The illuminance profile (lux) / daily pattern as compared to the standard of IES and MS 1525, (a) Scenario B1 and B4, (b) Scenario B2, (c) Scenario B3 and W5, (d) Scenario B5

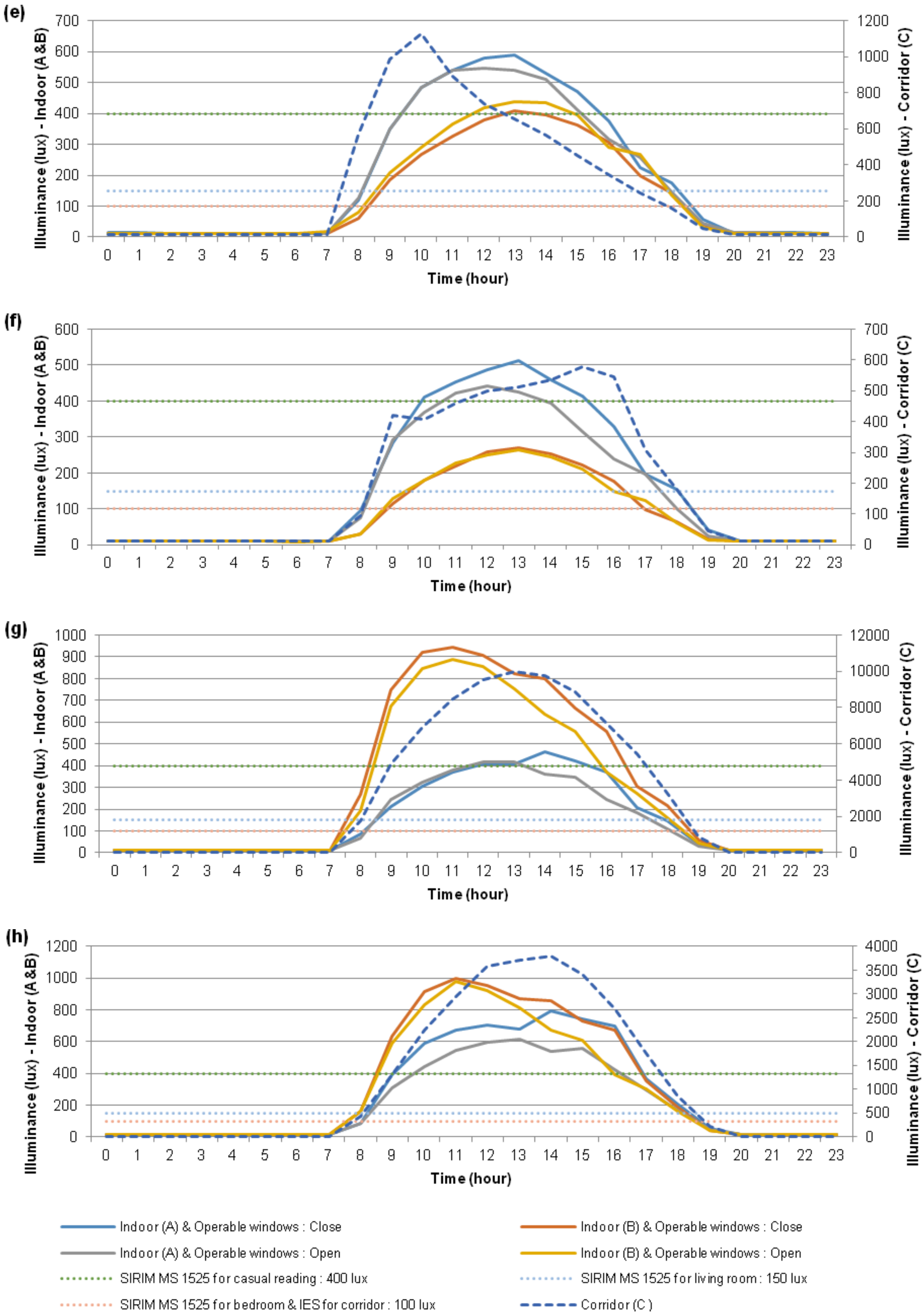


Figure 5. continued, (e) Scenario W1, (f) Scenario W2, (g) Scenario W3, (h) Scenario W4.

Table 2: The mean and maximum illuminance values (lux) in the room and corridor according to the level of the floor.

Level & Room No.	Scenario		Location		
			Indoor A	Indoor B	Corridor
Level 4, 406	W3	Direct contact with man-made surfaces on the top	139 lux Max: 682 lux	278 lux Max: 1,644 lux	3,120 lux Max: 14,179 lux
Level 3, 306	B1 & B4	North orientation & Avoid direct contact with man-made surfaces on the ground	91 lux Max: 453 lux	187 lux Max: 966 lux	2,647 lux Max: 12,933 lux
Level 3, 319	W1	East orientation	185 lux Max: 721 lux	136 lux Max: 643 lux	282 lux Max: 3,189 lux
Level 3, 315	B2	South orientation	127 lux Max: 509 lux	76 lux Max: 359 lx	3,848 lux Max: 18,893 lux
Level 3, 311	W2	West orientation	151 lux Max: 635 lux	82 lux Max: 398 lux	192 lux Max: 1,133 lux
Level 2, 208	B5	Shaded	37 lux Max: 162 lux	65 lux Max: 304 lux	422 lux Max: 1,943 lux
Level 2, 205	B3 & W5	Avoid direct contact with man-made surfaces on the top/ Exposed	93 lux Max: 461 lux	128 lux Max: 580 lux	1,750 lux Max: 8,794 lux
Level 1, 102	W4	Direct contact with man-made surfaces on the ground	221 lux Max: 1,131 lux	286 lux Max: 1,407 lux	1,097 lux Max: 5,452 lux

Referring to Table 2, the mean illuminance values in the room varied from 37 lux to 286 lux, while in the corridor area the values were between 192 lux and 3,848 lux. Comparatively, higher mean illuminance values were recorded in the corridor as compared to the rooms exceeding 3,120 lux. The selected rooms which represented the worst scenarios recorded higher mean illuminance values with the margin 6 to 150 lux, as compared to the rooms that represented the best scenarios. However, a different situation was recognised for Indoor B between scenario W1 (east orientation) and scenario B1 (north orientation). The mean illuminance value for B1 was 51 lux higher than W1. Overall, the highest mean illuminance values for both Indoor A and B were recorded in the room that represented scenario W4 (direct contact with man-made surfaces on the ground). The highest maximum illuminance values for Indoor A and B were recorded in the rooms which represented scenario W4 (direct contact with man-made surfaces on the ground) with 1,131 lux and W3 (Direct contact with man-made surfaces on the top) with 1,644 lux, respectively. As located at the middle of building, the corridor of the room which represented scenario B2 (south orientation) showed the highest mean and maximum illuminance values with 3,848 lux and 18,893 lux, respectively.

DISCUSSION

Higher mean illuminance values were recorded in the corridor to compare the rooms (Table 2). The adequacies of daylight with regard to the minimum requirement of the IES for corridor; 100 lux, were from 8 a.m. to 7 p.m. (Figure 5). Thus, this reduces the electricity usage for artificial lighting in the corridor area. As presented in Figure 5(f), the availability of daylight at the corridor of the room, which is representative of scenario W2 (west orientation) was limited from 8 a.m. to 6 p.m. although this room is orientated to the west and supposedly receives the most sun in the mid-afternoon (Al-Obaidi and Woods, 2006). This is due to the shading effect of the large tree canopy as adjacent to the 'Rimba Ilmu' area. In order to improve the daylight illumination in a shaded corridor area, optical systems can be adapted as alternative design strategies by redirecting daylight to areas which are further from the internal courtyard (Kischkoweit-Lopin, 2002). The success of these optical systems includes the following traits; angle selective glazing, light guiding shades, vertical and horizontal light pipes, switchable glazing and angle selective skylight, all of which have been proven relatively in small buildings by Edmonds and Greenup (2002).

According to Yeang (2008) and Zain-Ahmed (2009), these systems designed and effectively transported the daylight to block direct sun, direct source of glare and thermal discomfort.

Different illuminance values were recorded even within the same room, which can be well visualised in Table 2 and Figure 5. The side of the room's wall facing to the east had received more daylight due to the sun path. There were different times and periods of daylight availability with regard to the minimum requirement of MS 1525 for casual reading; 400lux in the rooms. Prolonged period was recorded in the room that represents scenario W3 (direct contact with man-made surfaces on the top). The duration reached up to 9 hours, starting from 8 a.m. to 5 p.m. daily [Figure 5(g)]. The duration and the amount of daylight received gradually decreased from the top to the second floor. This is more obvious on the second floor with 6 hours of duration [Figure 5(c)]. However, the duration of daylight received on the first/ground floor increased up to 8 hours in the room which represents scenario W4 (direct contact with man-made surfaces on the ground) [Figure 5(h)]. The mean and maximum illuminance values were much higher as compared to the values for the room on the top floor, where the values at the both sides of the walls being slightly similar (Table 2). The same results were also discovered as compared to the room that represents a contrasting scenario B4 (avoid direct contact with man-made surfaces on the ground) [Figure 5(a)]. These are due to the fact that there are no overhangs over the windows and due to the reflection of solar radiation on the concrete paving (Lechner, 2009).

As an intermediate room, the adequacy of daylight in the room that represents scenario B2 (south orientation) had fulfilled the minimum requirement of MS 1525 for casual reading [Figure 5(b)]. Apparently, it was only limited to four hours from 10 a.m. to 2 p.m., even when there was a high value of light intensity in the corridor area which was exceeding 18,000 lux (Table 2).The corridor area is directly facing the internal courtyard. Referring to the rooms representing scenario W1 (east orientation) and W2 (west orientation) which are located on the same floor, these two corner rooms received higher amounts of daylight for longer durations; that is up to eight hours [Figure 5(e)& (f)]. Meanwhile, only 1,000 lux to 3,000 lux were recorded in the corridors of both corner rooms, as a result of not facing the internal courtyard area (Table 2). These substantial differences occur due to the wide overhangs over the windows all along the floor. The presence of the opening wall to encourage wind pressure inside the room has limited the function of transom over the doorway to provide the penetration of daylight from the internal courtyard into the intermediate room. The artificial lighting is needed to deal with the shadows inside, which are caused by the overwhelmingly efficient solar protection and shades (David et al., 2011). Therefore, the use of wide overhangs all along the floor and the opening wall inside the room should critically be analysed, especially for the intermediate room. The efficiency of solar shades must be considered both for thermal and visual points of view, plus good solar shade typically excludes all direct sun and much of the indirect light from the sky as well (David et al., 2011). An appropriate sun shading device for the window is necessary to reject the undesirable amount of solar radiation but at the same time, it lets the desirable amount of solar radiation to penetrate the aperture for daylighting purpose (Chung et al., 2010). In addition, the indoor space should be kept open as frequently as possible by reducing the number of walls, as well as daylight penetration, to encourage air circulation inside the room (Tantasavasdi at al., 2001).

Located on the same floor, there is an intermediate room that represents two different scenarios; B1 (north orientation) and B4 (avoiding direct contact with man-made surfaces on the ground) [Figure 5(a)]. Theoretically, the illuminance value is slightly similar to the room that represents scenario B2 (south orientation) [Figure 5(b)]. Apparently, a higher mean and maximum illuminance value with longer duration of daylight availability had been recorded, that is up to eight hours. Meanwhile, at the corridor area, the value is slightly lower with the same duration of daylight availability. Different conditions of the area facing the room are hypothesised as the justification for this situation. There is a green area with trees at the south, while a multipurpose open area is located at the north of the residential building.

The presence of a landscape with green trees influences the surrounding environment as compared to the open sky (Monteiro and Alucci, 2009).

The amount of daylight in the room which represents scenario B5 (shaded by landscape or trees or adjacent buildings with north-south building orientation) was less than the minimum requirement of MS 1525 for casual reading [Figure 5(d)]. As shaded by trees with large canopy, the maximum value of daylight was only 304 lux (Table 2). The contribution of the green landscape in providing better environment is undeniable. The tree canopy has a significant filtration capability which contributes to the reduction of terrestrial radiation, cooling the ground surfaces by capturing more latent heat, reducing air temperature by promoting more evapotranspiration, and effectively improving the outdoor thermal comfort, especially in open spaces of the tropical climate region (Hyde, 2000; Monteiro and Alucci, 2009; Shahidan et al., 2010). Unfortunately, too much shade will evade the effectiveness of daylighting in the building. Thus, in optimising the utilisation of landscape and the trees to improve the condition of the room through shading effects, the visual comfort should not be sacrificed as well. Relatively, the illuminance in the room which represents the opposing scenario; W5 (exposed to open space with north-south building orientation) is much better [Figure 5(c)].The adequacies of daylight with regard to the minimum requirement of MS 1525 for casual reading; 400 lux, was from 10 a.m. to 4 p.m. with the maximum exceeding 500 lux. This room was also representative of scenario B3 (avoiding direct contact with man-made surfaces on the top) and as parallel with the opposing scenario which has been discussed earlier, the values of light intensity at W3 were found to be much higher with a longer period of time that meet the requirements of MS 1525 for casual reading.

According to the contradiction between the usages of some bioclimatic design strategies, the green landscape has more negative impact on the adequacy of daylight in the room, as compared to the overhangs along the windows and wall opening in the windows. In the room E 208, which happens to be shaded by a tree with large canopies, it has recorded low illuminance values. The maximum value was only 304 lux and not exceeding the minimum requirement of MS 1525 for casual reading. In turn, the illuminance values in the intermediate rooms with wide overhangs over the windows all along the floor were much higher with the maximum illuminance value 966 lux. The adequacy of daylight with regard to the minimum requirement of MS 1525 for casual reading was beyond 4 hours daily. The wall opening has less negative impact on the adequacy of daylight in the room. Some of the rooms studied recorded higher illuminance values, exceeding 1,000 lux and fulfilled the minimum requirement for casual reading for more than 6 hours daily. This negative impact was only discovered on selected rooms, depending on their location and orientation.

Overall, the adequacies of daylight in all selected rooms have fulfilled the minimum requirement of MS 1525 for the living room (150 lux) and bedroom (100 lux) most of the daytime. Then, there are the constant minimum values in the rooms and the corridors due to the corridor and street lamps located in close proximity to one another in the selected rooms. The corridor and street lamps are switched on from 7 p.m. to 7 a.m. daily.

With the opening of operable windows, the iluminance values were slightly reduced as revealed in Figure 5.The usage of plastic net with 1.5 cm of mesh size for security reason during the measurement has influenced the adequacy of daylight in the room. However, there were no differences in the room on the ground floor that can represent scenario W4 (direct contact with man-made surfaces on the ground) [Figure 5(h)]. The plastic net was not used in this room as the window grill was already fixed with 4 cm of mesh size iron net prior to this measurement. Therefore, the use of the window grill or net for security purposes should be well planned beforehand, to avoid the reduction of daylight level, as well as to promote natural ventilation in the room (Aynsley, 2007).

CONCLUSION

The application of bioclimatic design strategies based on an internal courtyard arrangement at a residential college building in a region with tropical climate is able to provide a comfortable room with less electricity usage, particularly for the lighting purposes.

According to the illuminance profile (lux) / daily pattern, the daylight is available at 7 a.m. until 7 p.m. daily and reaches the peak between 12 p.m. and 1 p.m. due to the location of the rooms. There are different amounts of daylight in the room in the residential college building with the internal courtyard arrangement, even within the same room. The side of the room's wall facing to the east had evidently received more daylight due to the sun path, in the range of 23-51% as compared to the west. The daylight availability in terms of the duration and amount is gradually reduced by lowering the floor levels, and is considerably increased at the ground floor due to the absence of overhangs over the windows and the reflection of solar radiation. These findings are based on the measurement that was conducted in eight unoccupied student rooms, which are regarded as the most excellent rooms in representing ten scenarios due to limited access to the residential block based on safety issues.

The residential college building design, which is based on the internal courtyard of the building arrangement and well adapted to other bioclimatic design strategies, has been found to be able to provide a comfortable room as a living space and a bedroom. This type of building design and strategies; specifically transom/fixed opening over the doorway of the room, open staircase area, two types of single glazed window with standard float and tinted glass, glare protection and adjustable natural ventilation options, should widely be implemented either for refurbishment or as new designs of any residential college building. The internal courtyard provides the adequacy of daylight at the corridor, which is up to ten hours daily. Thus, electricity usage for lighting in the building is reduced, especially in the tropical climate region that receives 12 hours of daylight every day and all year round. However, further improvements are needed when the minimal daylight is required for the study room; especially for casual reading, we remember that the daylight is only limited for a certain duration of time. This involves a critical evaluation on the design and the usage of overhangs over the windows by considering the room location and orientation. Also, the wall opening in the room theoretically creates wind pressure only with the presence of high air velocity while denying the distribution of daylight entirely. Additionally, the optimal landscape designs for daylighting in buildings should take into account the tree height, crown shape and distance to the buildings.

In order to evaluate the penetration and distribution of daylight in a systematic and rigorous manner, future research should include more rooms and not only limited to a certain area and period. Referring to this study; which emphasizes on a multi-level residential college building with an internal courtyard of building layout and single external wall, all the intermediate and corner rooms on each floor should be included in this evaluation. The service areas such as the bathroom, toilet, store and staircase areas are also considered essential to be examined. Additionally, the surface reflectivity factor should be highly considered as well. Thus, the effectiveness of bioclimatic design strategies in influencing the daylight penetration and distribution in the building can be determined precisely. The validation of findings from the field measurement can be done by using computer simulation.

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