The Learning Impact of a 4-Dimensional Digital Construction Learning Environment

Chris Landorf, Stephen Ward

***Abstract*—**This paper addresses a virtual environment approach to work integrated learning for students in construction-related disciplines. The virtual approach provides a safe and pedagogically rigorous environment where students can apply theoretical knowledge in a simulated real-world context. The paper describes the development of a 4-dimensional digital construction environment and associated learning activities funded by the Australian Office for Learning and Teaching. The environment was trialled with over 1,300 students and evaluated through questionnaires, observational studies and coursework analysis. Results demonstrate a positive impact on students' technical learning and collaboration skills, but there is need for further research in relation to critical thinking skills and work-readiness.

***Keywords*—**Architectural education, construction industry, digital learning environments, immersive learning.

I. Introduction

WORK-INTEGRATED learning has been suggested as a means to enhance student learning through the application of theoretical knowledge in a real-world context [1], [2]. While the integration of academic theory with the practice of work provides recognised benefits for learning and employability, the design of pedagogically sound curriculum that delivers equitable educational experiences for large student cohorts remains an elusive goal [3]. This is particularly so for students in construction-related professional disciplines, such as architecture and engineering, where structured industry-wide placement programs are limited and access to building sites to contextualise learning is a problematic issue [4].

Recent developments in work-integrated learning have, however, started to explore alternative approaches to traditional on-the-job training methods [5]. One of these alternative approaches involves the simulation of realistic work situations using problem-based learning pedagogical models supported by digital technology. This approach offers the dual benefits of replicable and structured educational experiences, and a safe and supportive learning environment.

Rather than using a digitally constructed virtual reality, this paper reports on an Australian Office for Learning and Teaching funded project that uses photographic surveys of a live construction site as the basis for a digital learning environment. The paper describes the development of an interactive 4D Construction Learning Environment that provides access to 75 high-resolution, 3-dimensional digital photographic surveys undertaken at weekly intervals (four dimensions) during the construction of the University of Queensland's Advanced Engineering Building in Australia. The 4D environment incorporates additional resources associated with construction including technical drawings, contract administration documents, time-lapse videos and interviews with project personnel. The paper also examines the design and impact of a variety of innovative learning activities and assessment strategies developed in association with the learning environment.

II. The Project Context

A recurring theme in higher education has been the need to maintain a balance between the academic theory delivered in classrooms and the application of that theory in a real-world context. Work-integrated learning or the "intentional integration of theory and practice knowledge" is one approach that seeks to address the application disciplinary knowledge and skills by students in a real-world context. The purpose of work-integrated learning is universally understood to ensure university graduates are immediately effective in their chosen professional setting or work-ready [6].

However, disciplines that have traditionally relied on informal internship and industry placement programs to develop practical graduate skills have been tested by the rapid expansion of higher education in the twentieth century [7]. Unlike the medical and teaching professions, disciplines such as architecture and engineering do not provide work placement programs funded as an integral part of a higher education qualification. This has placed stress on both professional expectations for work-ready graduates, and on student expectations for pre-graduation work experience. A further factor to consider in construction-related disciplines is the inherently dangerous nature of construction sites [4]. This combined with the fragmented and adversarial nature of the construction industry, impacts on the ability of practitioners and educators to contextualise student learning through large-group site visits or individual work placements [10], [11].

The development of skills in communication, teamwork, planning and organising, creative problem-solving and critical thinking, self-management, life-long learning, and initiative and enterprise are some of the attributes identified as critical in work-ready graduates [8]. They are also attributes whose development is most often associated with the experiences gained through work-integrated learning. This suggests an

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opportunity to explore alternative technology-enhanced approaches as a means to providing real-world experiences for large student cohorts while maintaining pedagogical rigour and educational validity [5]. Capacity to work in a team, problem-solve and think critically are particular attributes that also require significant curriculum transformation. Addressing the development of these attributes requires a comprehensive and systematically re-thinking of learning objectives, teaching strategies and assessment methods and staff training [9].

III. The Project Background

In December 2013, a team of academics from architecture and civil engineering at The University of Queensland (UQ), construction management at The University of Newcastle (UoN), and architecture at the University of South Australia (UniSA) was awarded an Australian Government Office for Learning and Teaching (OLT) Innovation and Development Grant. The grant was awarded to development of an interactive, interdisciplinary 4D digital learning environment and aimed to address problems associated with the provision of a realistic, practical and interdisciplinary experience for students in construction-related professional disciplines.

The project used an existing series of 75 high-resolution, 3-dimensional digital photographic surveys undertaken at one- to two-weekly intervals (four dimensions) throughout the construction of UQ's Advanced Engineering Building, a AU$133 million teaching, laboratory and office facility designed to a achieve an Australian 5 Star Green Star rating for sustainable design performance (6 Star equates to World Leadership). The 75 surveys had been processed into an initial 4D environment prototype called the 4D Construction Learning Environment Version 1. Version 1 provided self-directed access to the 75 photographic surveys, visually capturing the construction process over time.

The OLT project set out to expand the prototype's usability and expand its functionality by incorporating other resources associated with the design and construction of the Advanced Engineering Building, including drawings, contract documents and time-lapse videos. The project also set out to integrate 'factional' contract and project management resources, and interviews with key members of the design and construction project team, to enhance the real-life context. These improvements expand the existing 3D images into a multi-user 4D environment. Learning activity case studies were also developed to describe the various teaching approaches trialed as part of the project. These approaches vary from using the 4D environment as a simple demonstration tool during a conventional on-campus lecture through to simulating problems to activate student learning [12], using a collaborative problem-based learning approach to enhance critical thinking skills [9].

IV. The Project Approach

A. Conceptual Approach

The project adopted a 'exploratory learning' conceptual model derived from Kolb's four-stage 'experiential learning cycle' [13], [14]. Kolb's original experiential learning model defined a cycle of learning that moved from [a] concrete experience, to [b] observing and reflecting on that experience, to [c] forming abstract concepts in response to the experience, to [d] testing concepts in new situations that in turn become [a] concrete experiences. Experience in Kolb's model relates exclusively to 'lived' experiences. However, technology-enhanced learning approaches can provide virtual experiences gained through 'transactional' learning, or choreographed problem-based learning tasks that can also incorporate team-based learning.

TABLE I
Summary of Participating Courses and Learning Activities

Course Description and Format	Learning Activity
Year 1 Bachelor of Construction Management, UoN Building Codes and Compliance (250 students mixed-mode delivery)	Evaluation of fire safety issues in an immersive learning context. Formal evaluation of student comprehension using codes, construction drawings and 4D environment.
Year 1 Bachelor of Construction Management, UoN Construction Technology 1 (350 students mixed-mode delivery)	Demonstration of site safety and construction processes in a lecture context. Indirect assessment of student comprehension using construction drawings and activity sequencing in the 4D environment.
Year 2 Bachelor of Engineering Reinforced Concrete Structures and Concrete Technology, UQ (250 students on-campus delivery)	Demonstration of concrete design and construction processes in a lecture context. Formal evaluation of student comprehension using construction drawings and activity sequencing in the 4D environment.
Year 3 Bachelor of Architectural Design, UQ Architectural Technology 5 (100 students on-campus delivery)	Evaluation of building codes, structural, environmental and construction issues in an immersive learning context. Formal evaluation of team-based comprehension using construction drawings and activity sequencing in the 4D environment.
Year 3 Bachelor of Architectural Studies, UniSA Architecture and Technology (100 students on-campus delivery)	Demonstration of services and sustainable design integration in an immersive learning context. Formal evaluation of team-based comprehension using construction drawings and the 4D environment.
Year 3 Bachelor of Construction Management, UoN Construction Business Management (150 students mixed-mode delivery)	Evaluation of management actions in an immersive learning context. Formal evaluation of student comprehension using role-play, reflection, factional contract documents and the 4D environment.
Year 2 Master of Architecture, UQ Architectural Practice 2 (65 students on-campus delivery)	Evaluation of contract administration issues in an immersive learning context. Indirect assessment of team-based comprehension using factional scenarios and the 4D environment.

To incorporate virtual experiences into the conceptual framework for the project, Kolb's second stage was separated into exploration and reflection stages, creating a five-stage model that emphasised the expanded role of social interaction in the immersive learning experience. Within this framework, the 4D environment was used in a variety of ways across four disciplines and seven courses, from a self-directed learning resource to an immersive learning environment. A summary of the participating courses, programs and learning activities is provided in Table I. A five-item Likert-type scale and open-ended evaluation questionnaire was administered to students in five of the seven courses, and in one course in consecutive years. Additional evaluation was undertaken in the form of in-class observational studies and analysis of assessment work.

B. *Research Methodology*

An action research methodological approach was adopted for the project to ensure a continuously reflective process of progressive problem-solving as issues emerged with software and pedagogical development [15], [16]. The project was divided into the four stages of approximately six months each.

1) Stage 1 Development (Semester 1 2014): This stage investigated alternative teaching approaches, software and interface design options, and access to construction documentation and key personnel. Existing course curricula were also reviewed.

2) *Stage 2 Usability Trial (Semester 2 2014):* This stage established how best to integrate additional resources into Version 1 of the 4D environment. New learning activities and assessment strategies were devised and a usability trial of Version 2 of the 4D environment was trialed, evaluated, reflected on and modified the environment to Version 3.

3) *Stage 3 Pilot Study (Semester 1 2015):* This stage oversaw the integration of other resources such as technical drawings, contract administration documents into the 4D environment. A Pilot Study trialing Version 3 of the 4D environment was also undertaken, evaluated, reflected on and the environment modified to Version 3.1.

4) *Stage 4 Evaluation (Semester 2 2015):* This final stage administered a further Pilot Study trial of Version 3.1, which was evaluated, reflected on and the environment modified to Version 3.2.

C. *Technical Specifications*

The 4D Construction Learning Environment was assembled from 75 time-lapse digital photographic surveys taken over the course of the construction of UQ's Advanced Engineering Building. The digital surveys were embedded in an existing GUI derived from Cameron et al. (2009). The resulting 4D environment prototype, Version 1 of the 4D Construction Learning Environment, was an offline, single-user application requiring access to Adobe® *Flash® Player* (a browser plugin for GUIs embedded in web pages) and approximately 80 GB of digital storage space.

A Nikon D200 digital SLR camera with an AF DX 10.5 mm fisheye lens was used for the photographic surveys. AF-S DX VR Zoom-Nikkor 18–200 mm and 55–200 mm digital lenses were used for general photographic work. Digital images were taken every one to two weeks over the course of construction. Images were taken from regular positions or 'nodes' spread horizontally and vertically across each level of the Advanced Engineering Building. Images were uploaded to a computer at the conclusion of each survey. Photographs taken at each survey node were stitched and rendered into large panoramic photos using AutoPano Giga V2.6 software. Internode and equipment hot-spotting, and Krpano panorama XML file exports were undertaken with PanoTour Pro V1.7 software. The 3D panorama functionality was provided by Krpano software. Finally, a unique Python script program was used to calculate node coordinates and the location of survey nodes on floor plans was achieved using Microsoft® OneNote® software.

Figs. 1 and 2 provide comparative screenshots taken from Version 3.2 of the 4D Construction website. Fig. 1 is taken from Level 2 of the building on 7 June 2011 and Fig. 2 is taken from Level 5 on 7 March 2012. Fig. 1 is taken at the edge of the construction site and Fig. 2 is taken from within the building itself. Students move chronologically between surveys using the horizontal timeline at the bottom centre-to-right of the screen. Horizontal navigation around each floor plate is managed via hotspots on the plan in the lower left of the screen and the vertical bar located between the plan and the timeline allows vertical navigation between floors. Each image can be rotated 360 degrees horizontally and vertically using a mouse. A mouse can also be used to zoom in to assess detail and enlarge the floor plan to assist navigation around the building. Finally, a drop down menu provides access to additional resources including construction drawings, contract administration documents and interviews with key personnel.

Fig. 1 Screenshot from the 4D Construction Learning Environment at Level 2 Node 6 dated 7 June 2011 [17]

Fig. 2 Screenshot from the 4D Construction Learning Environment at Level 5 Node 2 dated 7 March 2012 [18]

V. The Project Findings

An initial Usability Trial of the 4D Construction Learning Environment Version 2 was conducted with Year 3 Bachelor of Architectural Design students in Semester 2 2014. In-class, scenario-based activities were used each week for four consecutive weeks. Students worked in teams of 3-4 in a flat-floor active learning space with personal computers and Wi-Fi access. Students were asked to access the 4D environment and observe designated structural, environmental and construction issues. The aim was to use the 4D environment to engage students in team-based problem-solving, to reflect on how particular construction activities are carried out and specific building elements are fabricated. The aim was to also link the observed activities and elements to the 2-dimensional information communicated in construction drawings.

A Pilot Study trial of Version 3 of the 4D Construction Learning Environment was conducted in Semester 2 2014 with Year 1 and Year 3 Bachelor of Construction Management students, and Year 3 Bachelor of Architectural Studies students. The 4D environment was used as an in-class demonstration tool (Year 1 Bachelor of Construction Management), as an in-class demonstration tool and resource for self-directed student learning (Year 3 Bachelor of Architectural Studies), and as a context for immersive problem-based learning (Year 3 Bachelor of Construction Management). Additional trials of Version 3.1 were conducted in Semester 2 2015. The 4D environment was used as a context for immersive problem-based learning (Year 1 Bachelor of Construction Management), as an in-class demonstration tool and resource for self-directed student learning (Year 2 Bachelor of Engineering and Year 3 Bachelor of Architectural Design), and as a context for immersive problem-based learning (Year 2 Master of Architecture). A five-item questionnaire was administered to students. The questionnaire included four Likert-type scale responses and three open-ended questions. Results are summarised below.

A. *Question 1 Appearance*

Question 1 asked 'Did you like the appearance of the learning environment?' Responses included 36.6 per cent of students who strongly agreed, and a further 55.2 per cent of students who agreed with the question (as shown in Fig. 3).

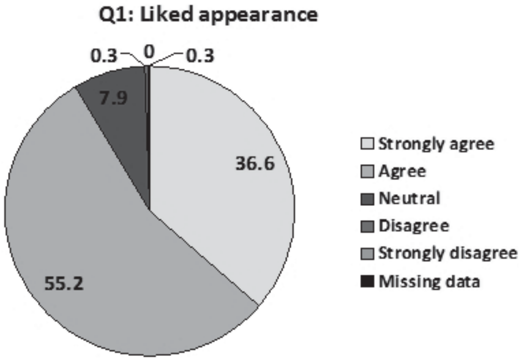

Fig. 3 Responses to student evaluation Question 1

Positive open-ended responses were made about the realistic appearance of the site, rather than the appearance of the environment itself. Suggestions for improvement in the Usability Trial included increasing the size of the floor plan in the viewing pane and enabling different floor plans to be overlaid to show the relationships between them. This was addressed in Version 3 of the environment. Negative comments were also made about the use of inconsistent nodal positions in each survey. Consistent nodal positions from one survey to the next would enhance user orientation but the variable progression of construction activity and on-site logistics makes this a difficult undertaking.

B. *Question 2 Navigation*

Question 2 asked 'Did you find the learning environment easy to use?' with 26.2 per cent of students indicating that they strongly agreed, and a further 54 per cent of students agreed with the question (see Figure 4).

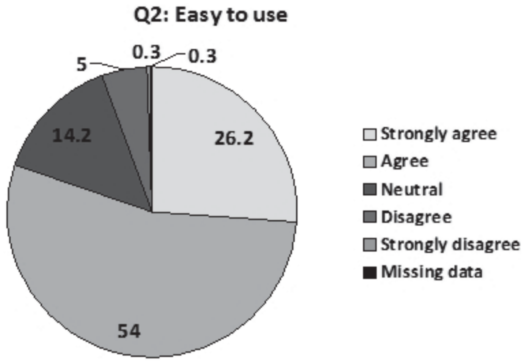

Fig. 4 Responses to student evaluation Question 2

Navigation, or ease of use, generated significant negative comment in the Usability Trial. Students considered the environment to be intuitive but 'slow to load', and that it 'froze', 'stuttered' or 'crashed' during use. The chronological survey selection function and the node selection function on floor plans were similarly problematic. These basic functionality issues were address in Version 3 and fewer negative comments were recorded in the Pilot Study. However, issues with the inconsistency of node locations from survey to survey remain unresolved.

C. *Question 3 Content*

Question 3 asked 'Did you find the learning environment assisted your understanding of architectural technology/construction management, if so, why?' with 21 per cent of students indicating that they strongly agreed with the question, and a further 58.4 per cent of students agreed with the question (as shown in Fig. 5).

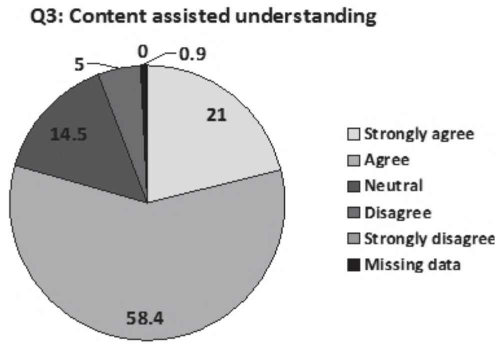

Fig. 5 Responses to student evaluation Question 3

The positive impact of the learning environment on students' understanding of the construction process was almost universally supported in both the Version 2 Usability Trial and Version 3 Pilot Study. Open-ended responses to Question 3 indicated that the 4D environment was a useful tool for understanding the day-to-day operation of a construction site and provided more information than static 2D photographs and one-off site visits. Positive feedback was provided about enhanced understanding of construction sequencing and the practical requirements of construction activities and building elements. Additional comments indicated that the zoom feature enabled valuable close examination of particular details, revealing building structure and architectural detail. Students also indicated that the 4D environment aided comprehension through comparison because they could compare 2D construction drawings and 3D images. Suggestions for improvement included incorporating time-lapse videos of key construction processes to help bridge the one- to two-week gap between digital surveys.

D. *Question 4 Learning experience*

Responses to Question 4 'Did you find the learning environment enhanced the architectural technology/construction management learning experience, if so, why?' included 17.7 per cent of students who strongly agreed with the question, and a further 55.2 per cent of students who agreed (as shown in Fig. 6).

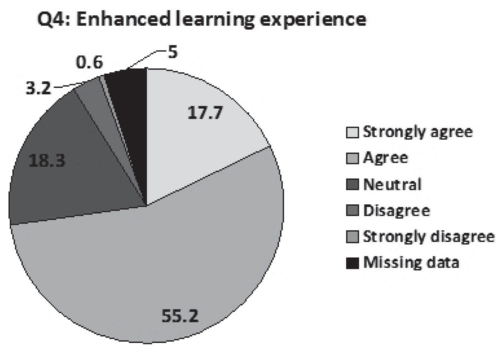

Fig. 6 Responses to student evaluation Question 4

Analysis of the open-ended responses to Question 4 revealed several themes to extent that the 4D environment enhanced the learning experience. Respondents indicated that 4D environment created a positive link between theory and practice by 'bringing the construction process to life', and consolidating theoretical lecture material through the exploration of a real-world setting. Some respondents suggested concepts explained in lectures became easier to visualise 3-dimensionally after using the 4D environment. Respondents in the Usability Trial also commented that the 4D environment helped to facilitate collaborative discussion and team-based problem-solving, which in turn enhanced their understanding of lecture content and their enjoyment of the learning process. The capacity to independently revisit the site, to follow specific aspects of the construction process over time, and to have instant access from the classroom to the construction site were also considered a positive.

Suggestions for improvement in the Usability Trial included more defined learning tasks with clearer aims and links to assessment. A guided tour was suggested, and giving more detailed whole-of-class explanations of construction processes and building elements as students using the 4D environment discover them. Respondents in the Pilot Study found the site to be a useful interactive visual aid that enhanced their comprehension, while the capacity to view 2D and 3D information together enhanced their understanding.

E. *Question 5 Improvements*

Question 5 was an open-ended question that prompted students to offer suggestions for future improvement. Suggestions from both the Usability Trial and the Pilot Study trials included developing the 4D environment for use on a mobile tablet and providing additional building case studies of various scale and complexity. Students commonly requested using consistent node positions on each floor and across each survey and including call-out labels to explain key construction processes and building elements.

VI. Discussion and Conclusions

As a means to achieve a balance between theory and practice, work-integrated learning, has become a debated approach in higher education. Work experience has had a long tradition in professional education. However, the pressure of student numbers and the difficulties associated with maintaining pedagogical rigour in workplace settings have had an impact on the opportunities available for students to spend time in real work environments that are relevant to their degrees. Workplace health and safety concerns have an additional impact on student access to 'live' building sites in construction-related professions.

This paper has argued that there are opportunities within this context to examine simulating real-life settings as an alternative approach to providing the benefits of work-integrated learning for students. Although studies have explored computer-simulated virtual reality environments, none have focused on the development of a 4D digital learning environment based on a 'live' construction project. The project detailed in this report provides such an environment.

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The 4D Construction Learning Environment has been well received by academics and students in four different programs at three institutions. For academics, the possibilities offered by the 4D environment range from its use as a simple demonstration tool suitable for use in a conventional on-campus lecture through to a comprehensive, immersive, problem-based learning scenario and assessment system requiring engagement with the full array of resources offered within the environment (4D images, drawings, contract documents, time-lapse videos and interviews). The 4D environment has also been shown to be an effective tool across different disciplines and year levels.

For students, the project evaluation evidence indicates that the 4D environment can be used effectively within existing course aims and professional accreditation structures to improve learning outcomes. The 4D environment was found to enhance students' understanding of construction processes, and to give them a means to learn collaboratively and contextualise theoretical material.

It is apparent, however, that using the 4D environment as a simple visual aid represents a shallow engagement with the pedagogical possibilities that it offers. While there are issues, such as the dependence on predetermined survey nodes and the consistency of node locations from survey to survey, the 4D environment can provide a genuine, flexible and cost-effective improvement over traditional lecture-tutorial activities, but only when it is fully utilised and holistically integrated into the curriculum.

'Virtual' work-integrated learning has the potential to satisfy, at least in part, student and employer demand for a balance between theory and practice, as well as to provide work-ready graduates who have the capacity to engage immediately in their chosen professional settings. The benefits are, however, contingent upon the skilful integration of immersive learning scenarios into those parts of the curriculum where their full benefit can be realised.

This project provides one building case study. It is important to note that the 4D Construction Learning Environment could host additional case studies of different building types and scales. The 4D environment could also host additional self-directed and discipline-specific tutorials with pop-up text boxes to explain elementary technical terminology and construction processes. Together with further dissemination activities, such a development of the 4D environment would enhance the adoption of the resource across disciplines, programs and year levels.

Finally, this project has identified four associated areas that warrant further exploration. The project has shown that the 4D environment has the capacity to enhance and contextualise student learning; however, its impact on the development of critical thinking skills and work-readiness needs further, targeted investigation. Secondly, the project has led to the design of a variety of innovative learning activities and assessment strategies that enable the integration of the 4D environment across different disciplines and year levels. There is significant scope to develop and evaluate additional creative teaching approaches. Thirdly, the application of 3D laser scanning technology and advances in virtual reality software are areas of growing interest within the construction industry, as well as allied areas such as archaeology, heritage management and town planning. There is an opportunity to investigate the integration of this technology and software into further iterations of the 4D environment. Lastly, the 4D environment currently hosts one case study of a complex educational building type, the Advanced Engineering Building at the University of Queensland, Australia. There is an opportunity to enhance the adoption and impact of the 4D environment through the inclusion of additional case studies of different building types, scales and geographical locations.

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