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THE USE OF 3D AND 4D CAD SYSTEMS TO REDUCE ERROR RATE AND REWORKING IN CONSTRUCTION

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ABSTRACT

Currently much work on 4D CAD concerns its use as a design tool, this paper will explore its uses as a construction management and construction education tool. 3D and 4D CAD systems offer the potential to reduce several areas of miscommunication between designers, engineers, fabricators and builders. The particular kind of error resulting from discrepancies between plans and elevations may be expected to be eliminated with integrated 3D CAD. Omissions should be reduced due to the cross checking inherent in 3D and 4D CAD systems. Errors that result from the failure of any of the players to fully visualise the 3D object should also be greatly reduced. The facility with which 4D CAD enables dry runs of the construction process to be tried out should reduce those errors resulting from a failure to appreciate the order of construction operations.

Design or construction errors that result in rework cost the industry both in the value of the rework itself, as well as in the time delays caused. Improved visualisation techniques will address the documentation quality issue which is a perennial problem in the construction industry. 4D CAD has a particular application in the education of the workers involved in the construction process. Complex geometrical and structural objects can be displayed in a way that is readily accessible to all participants and not just to those who are able to visualise the solid object from its representation in plan and elevation. The result of widespread industry adoption of these tools is anticipated to be greater efficiency and predictability in the process from documentation to completion.

Keywords : Construction industry, housing, training, 4D CAD, simulation

1. INTRODUCTION

Although the residential construction industry in Australia is a significant slice of the national economy in dollar terms, it has been slow to adopt new technologies. This research aims to show that productivity gains and improvements in end-user satisfaction can be made by the adoption of integrated computer based training and documentation systems. Although the home building process has tended to remain resolutely "low-tech", this has not led to a lack of defects or a low rate of necessary reworking. In fact, consumer dissatisfaction with the products of the home building industry is at a high level, and complaints about shoddy workmanship and the cost of repairs are rapidly increasing. Of course, shoddy workmanship can have other causes apart from failure to properly communicate the task at hand to the construction worker. Inadequate time allocation, pressure of ongoing work schedules, lack of adequate supervision and even deliberate sabotage may all contribute to poor quality results (Tilley 1997). The use of training and documentation based on animated CAD modelling may be expected to reduce or eliminate at least those defects that are due to discrepancies, omissions and simple mistakes in the drawings and specifications (Atkinson, 1998). In addition, the effect of animating the construction process is hypothesized to lead to a better level of understanding in the building worker, and therefore result in less reworking.

Research conducted at Virginia Tech on the topic "industrialising the residential construction site" (HUD, 2000) suggests that physical integration and information integration can enhance the productivity and performance of the residential construction sector. This can be achieved with the aid of object oriented CAD and information technology tools. With basic computing skills already on hand in most builder's offices, information integration (beginning with object oriented CAD systems) is likely be the key to addressing higher levels of physical integration (Sarshar et al, 2002). Performance gains may be realised by simply addressing information communication, an area previously identified as the source of problems.

Modern tools already in use in the manufacturing sector (e.g. Object Oriented 3D CAD, Robotics, and Information Technology encapsulating information originating from designers and constructors) are not yet widely integrated in a structured way within the construction industry (HUD, 2000). This research attempts to address this deficiency.

By way of explanation of some of these tools, it is necessary to look at definitions for the terms involved. 4D CAD is a term that has lately come into use in the construction industry. It is generally held to mean the integration of a 3D CAD model with a construction schedule, thereby adding the element of time to the 3D CAD document (Cory, 2001). Cory further states that 4D CAD focuses on "integrating the technical design information respectively within the design and construction phases". Dawood et al (2003) agree that 4D CAD planning consists of systems "where the process is visualised by building the 3D product model through time according to the critical path method". 3D CAD is thus converted to "virtual reality" simulation. 4D construction simulation or visualisation is described by Chau et al, (2003) as being "generated automatically via integrating the 3D geometrical model with the associated activity schedule". Clayton et al (2002) describe a process where architecture students are able to produce virtual construction by building "3D CAD models showing all components and animating them to illustrate the assembly process". Koo and Fischer, (2000) explain that a "4D CAD model results from the linking of 3D graphic images to the fourth dimension of time. In the 4D model the temporal and spatial aspects of the project are inextricably linked, as they are during the actual construction process". As a result of their case study, Koo and Fischer concluded that "… 4D CAD models are effective in evaluating the executability of a construction schedule" (Koo and Fischer, 2000). The proposed experiment in this paper will investigate whether 4D CAD models of construction tasks to be developed based on Koo and Fisher's study would help to improve the accuracy of construction as it is carried out.

Kamat and Martinez, (2002) make an important distinction between 4D CAD and "dynamic 3D visualisation of operation simulations". This, they say, attempts to do more than integrate 3D CAD models with scheduling. It also depicts "the interaction between involved machines, resources and materials". 4D CAD, they state, can depict the evolution of a construction project but not the interaction of resources that build it. This may well be an avenue worthy of future investigation. Furthermore, recent developments of software to perform various tasks have brought into currency the term "nD CAD". This is held to involve a 3D CAD model with various extensions that include scheduling, costing, structural sufficiency and automatic code checking (Rowlinson and Yates, 2003).

2. ADVANTAGES OF OBJECT ORIENTED CAD

It has been estimated that somewhere in the vicinity of 135 people, including order processors and shippers, are involved with the process of making a house from design to final inspection (HUD, 2000). Given that a house is the largest investment that most people make, changes are often requested during the construction phase. Among the many and varied causes of these changes may be the inadequate initial design or the failure by the participants to clearly understand the project from the documentation. Most changes require that the work stop, the changes be evaluated, existing work be removed, material be removed, new materials be ordered and installed, and schedules be pushed back. Recent developments in three-dimensional visualisation of buildings, linked to object-oriented CAD databases, are already enabling owners to view "their" house in its final colour, material, and upgrade configuration, with rapid pricing of changes (Evans, 1999 in HUD, 2000). This three-dimensional visual presentation can significantly reduce misunderstandings, avert owner-initiated changes and improve construction programming generally (Heesom and Mahjoubi, 2004).

2.1 AUSTRALIAN INDUSTRY RESPONSE

A survey was conducted among various construction industry personnel to gauge attitudes to, and interest in the various forms of CAD documentation. The survey sought responses from architects, building designers, quantity surveyors, building estimators, construction managers, project managers, builders and building surveyors.

Both email and personal interviews were used to seek responses. 87 surveys were sent out and 29 responses were received with a completed questionnaire (a response rate of 33%). The survey sought to ascertain whether the general response to the use of new technology in construction was positive or negative, and whether any pattern emerged in the responses

Generally, the response to many questions was significantly more negative than anticipated. There maybe several reasons for this. Most of the questionnaires were responses to unsolicited emails. It could be that those wishing to lodge a protest about CAD systems would make the time to respond. The percentage standard error for the individual questions ranged from 9% to 18% (Siegel 1988). It is noteworthy that on a number of the questions asked, the largest response was neutral. Comments indicate that this may, in fact, mean simply that judgement is reserved on the matter. No conclusions can yet be drawn. In other words, there is a considerable constituency waiting to be convinced of the value of new systems and ways of working.

Table 1 General Survey Response (29 responses)

Proposition	Total Positive	Total Neutral	Total Negative
1. 3D CAD is the way of the future	61%	32%	7%
2. 3D CAD is my preferred form	42%	29%	29%
3. 3D CAD leads to fewer drafting errors	39%	32%	29%
4. 3D CAD is easier for builders	42%	33%	25%
5. 3D CAD leads to fewer construction mistakes	36%	28%	36%
6. 3D CAD makes costing more accurate	29%	42%	29%
7. 3D CAD is useful for construction scheduling	50%	36%	14%
8. 3D CAD is useful for training design office staff	61%	32%	7%
9. 3D CAD is useful for training management staff	57%	32%	11%
10. Animated (4D) documentation would be useful for training workers	61%	22%	17%
11. 4D CAD would be useful in construction planning	54%	36%	10%
12. Accurate 4D CAD would make estimating more precise	29%	39%	32%
13. Residential building is resistant to increased computer use	29%	39%	32%
14. My current work method will not change in the next ten years	25%	18%	57%
15. The next ten years will see increased use of computers in residential building	86%	14%	0%

The response to proposition 1 indicated that a clear majority of those surveyed see 3D CAD as “the way of the future”. However, proposition 2, which sought to determine the level of current usage of 3D CAD systems in the respondent group had roughly 40% preferred users to 60% who prefer other options. It is clear, however, that a positive attitude to CAD usage was significantly more common among architects and building designers than among other professionals surveyed. Overall there was some scepticism that 3D CAD would lead to fewer discrepancy-type errors (proposition 3). Further research is necessary to determine whether this response correlated with negative answer to the second question.

Slightly less than half of the respondents agreed that 3D CAD was easier for builders to understand. Comments indicated that this was due to a widely held belief that it is the quality of the construction knowledge of the documenter that is crucial rather than the system used. This theme was also reflected in the responses about whether fewer construction mistakes or more accurate costing

would result from 3D CAD usage (proposition 5). Architects as a group were negative on this proposition in contrast to their general attitude.
The response was more positive from all groups on the use of 3D CAD for construction scheduling (proposition 7) and comments indicated that some of the extensions related to CAD systems could lead to the automation of some of the repetitive areas of construction planning. There was a definite positive response to the proposed use of 3D and 4D CAD for training purposes (propositions 8, 9 &10). This is an area that seems to have a ready market for well-developed reality-based construction modelling. Scepticism reasserted itself, however, on the question of whether 4D CAD could make estimating more accurate (proposition 12). Once again the industry remains to be convinced that such systems will work in practice. The survey shows widespread acknowledgment of the likelihood that the use of computer technology in residential building will increase in the coming decade (proposition 14). Furthermore there is considerable willingness to respond to this change. A large majority of respondents perceive that their own working methods will change in the next ten years (proposition 15). The standard error percentages for the overall group ranged from 9 % to 19%.

It is clear that despite some cynicism there are demonstrable advantages to be gained from the use of integrated IT systems in the residential construction industry. In particular, Object Oriented CAD documentation systems can have a number of positive effects for the industry (Anadol & Akin 1994). For example, the ready exchange of information on computer file between the various design and construction consultants can be expected to lead to fewer discrepancies in design documentation. Land surveyors, architects, structural and mechanical engineers are able to produce documents in the same format, so that conflicts of interest may be resolved at the documentation stage rather than on site at greater expense. Quantity surveyors can also have input at this stage with resultant better control over cost outcomes. This appears to be well recognised in the industry (Drogemuller, 1997).

Nevertheless there remains considerable resistance to the wholesale transfer of the industry to IT based work systems. There are a number of sources for this disquiet. Firstly, several industry sources in our survey stressed that it is the skill of the operator rather than the operating system that determines the quality of the documentation. “Garbage in –garbage out” was the refrain of several architects and quantity surveyors interviewed for this study. Jim Peet, senior principal of Widnall, Quantity Surveyors, stated that

> “In my experience (now over 45 years) and having developed computer systems for our own practice over the last twenty years, any form of drawing is only as good as the level of knowledge of construction of the person doing the drawing work by whatever method”.

In addition, some respondents believed that newer CAD systems could (temporarily) mask the skill level of the operator, and lead to documentation that appeared to be adequate when this was not in fact the case.

The second area of objection to the computerisation of the documentation process related to the constant updating of platforms and systems. This leads to an ongoing capital outlay in order to keep up with the latest technology and small business particularly finds this prohibitive. In addition, incompatibility of old and new systems and between platforms is a further difficulty that plagues small business. Some architects have chosen to remain outside the CAD revolution and continue to produce traditional documentation for this reason. This is an issue that needs to be addressed before further integration of computer technology into the construction industry can proceed (Heesom, 2004).

Thirdly, there is some concern among designers that many CAD systems fall short of their promise in terms of producing usable construction documents in 2D form. The kind of diagrammatic sections so easily produced by 3D CAD systems may not contain sufficient information to make them useful for structural and engineering services purposes (Dakan, 2001). One of our survey respondents, Vanovac Associates confirmed this opinion stating that although "We use 3D Studiomax for 3D modelling and animation. 3D documentation is not, in our opinion, very effective."

Finally, our contractual and legal system still makes it necessary to produce a 2D paper document than can be signed off as the "Contract Document". This tends to mean that some of the benefits of integrated transfer of information are lost when the legal system ties all parties to the initial document produced to establish the project. On the other hand some of the survey respondents did feel that resistance to implementing integrated IT throughout the whole construction industry was largely due to the inertia of established businesses. Many of these wished to go on operating in the manner they had first learnt when they started out in the industry.

There was broad agreement among our surveyed group that 4D animated documentation of construction processes could be a useful training tool. Furthermore it was believed that it might be useful in construction scheduling. Independent research has confirmed this (Kang 2001 and McKinney et al, 1998). However, the view was strongly expressed that the use of animated documentation for actual construction projects was likely to meet with firm resistance. Respondents suggested that experienced construction workers were certain to feel condescended to by such documentation and to believe that it impinges on their exclusive territory. There is a great deal of existing expertise in turning paper documents into finished buildings and this would be somewhat threatened by animated documentation that purported to tell a builder how to do his job. To borrow from the terminology used in the Building Code of Australia, it could be said that builders prefer "performance based" documentation that specifies the outcome required, rather than "deemed to satisfy" documentation that tells them precisely how to do it.

3. RESEARCH PROPOSAL AT UWS

Specifically, this proposed research aims to investigate whether object-oriented computer-aided 3D drawing (CAD) with the addition of the time element through animation (which is called 4D CAD in this study), can improve the level of understanding that construction workers have of a building project. Initially, this simulated object-oriented CAD will be used to indicate the individual steps of the construction process to students. The proposal is designed to validate the effectiveness of 4D documentation in on-site conditions. Work is proceeding in many places on the assumption that 4D CAD will provide better communication tool than traditional paper documents. This proposal seeks to test that assumption.

In the proposed pilot study a small two room Autoclaved Aerated Concrete panel (Hebel™) structure, will be modelled using 3D AutoCAD software integrated with a critical path construction schedule. The background and advantages to this object-orientated CAD followed by aims, plan and methodology of the research is presented below.

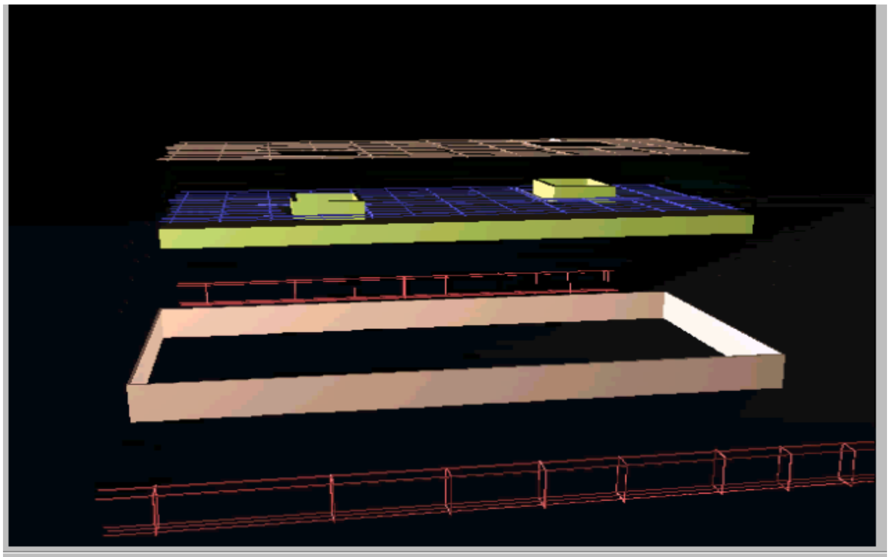
- This study aims to verify the supposition that the performance of workers and inspectors on a construction site can be improved through the adoption of modern computer aided technology. The functions of the workers and inspectors will be replicated using a group of second and fourth year building/construction management students. The two groups will clearly have varying levels of knowledge and experience, which will be quantified with initial questionnaires. Such varying levels of expertise are hypothesised to mimic a segment of the range that exists within the construction industry workforce generally.
- The study will be used to investigate the effects of the use of the CAD-oriented simulation on productivity and waste.
- This research will attempt to determine if some categories of information available to the worker or the inspector on site are particularly suited to the well-understood transfer of ideas.

In particular, this research aims to investigate whether object-oriented computer aided drawing (CAD), with the additional element of animation can improve the understanding of construction for all workers involved.

3.1 RESEARCH PLAN, METHODS AND TECHNIQUES

By using the '3D Viz' and 3D AutoCAD programs a small two room cabin will be developed into a 4D model. This model will consist of footings, floors walls with openings and flat roof. All the components will be developed separately and then assembled together with the assistance of animation software. Three-dimensional drawing files and an animated model will then be made available to the students for the construction and inspection of the cabin. A partially completed three-dimensional slab model as shown in Figure 1 used for a previous project is presented below. This model shows all the components of the slab including edge forms, top and bottom mesh, block-out forms, and edge beams reinforcements and develops work done on error rate in construction inspections (Saha et al, 1999). The aims, objectives and methodology of the proposed experiment are discussed below:

Figure 1: Components of a reinforced concrete slab in three-dimensional format



3.2 THE EXPERIMENT: INSPECTION & CONSTRUCTION OF AUTOCLAVED AERATED CONCRETE CABIN STRUCTURE.

3.21 Objective

The aim of the experiment is to investigate:

- Productivity and performance improvements due to 3D visualisation.
- The effect of experience/training on rate of detection of errors in a construction inspection.
- The effect of experience/training on cycle time (inspection time/construction time).

3.22 Method

Typical AAC panel components will be drawn using 3D viz and 3D AutoCAD softwares. This 3-dimensional drawing with cross sections and dimensions will be made available to the participants. Animated panel components showing step-by-step construction will be also made available to the students prior to physical construction. It should be pointed out that student body in the Bachelor of Building/ Construction Management course at the University of Western Sydney contains people with a wide variety of experience levels in the construction industry. Students include both part-time and full-time students. Many of them have significant industry experience, some have previous TAFE training and a relatively small number come directly from high school. As such they present a reasonable facsimile of the range of skill and experience likely to be encountered on a construction site.

This experiment will be imitating a typical construction site where an inspection approval is needed for an occupation certificate to be awarded. A number of students will be designated as workers and/or inspectors. These workers and inspectors will be divided into two separate categories before the start of physical construction namely, Category A and Category B

The Category A workers and inspectors will be exposed to a short presentation containing object-oriented 3D CAD drawings including step-by-step construction animation before the start of the cabin construction. The Category A workers and inspectors will be supplied with three-dimensional drawings containing plans, cross-sections, specifications and etc. The Category B workers and inspectors will be asked to build and inspect the cabin using traditional two-dimensional drawings. A group consisting of three construction workers from each category will be assigned to physically build the cabin. Inspectors will arrive on site after the completion of construction. Inspectors will be also provided with a standard checklist for monitoring the defects, the contents of which will available to all participants.

It is expected that 5 groups from each category will be involved to physically build the cabin up to the pre-occupation inspection. The cabin will be built by using standard Hebel panel materials in a replicated site condition. A number of second and fourth year Bachelor of Building/Construction Management students (enrolled in BG209A: Building in Practice 1 and BG413A: Quality Systems offered in spring semester) will be expected to participate in this research activity. Students will be only asked to assemble all structural components not render or finish off the job. Components of the cabin will be designed in such a way that building time for the cabin will not exceed six hours. Building in Practice 1 students are allocated to conduct six (6) hours of site work per week as part of their curriculum. Students (estimated forty inspectors) from the final year subject BG413A: Quality Systems (also offered in spring semester) are then expected to detect the most common errors arising from this type of construction (listed below). Activities performed for this research work are normally part of their major assignments. Therefore, it is expected that students will be motivated to participate in this project. This cabin construction and inspection task will last for 10 weeks, which will be scheduled during the spring semester (week 3 through to week 12).

After the completion of construction of cabin by second year students, each inspector (from fourth year students) will be provided with approved plans, drafted to industry standard (depending on their category), for the cabin and will be given a generous amount of time to inspect and report using a checklist based on current Australian Standards, with room for comments, on the following items as listed below.

- Correct number and accurate positioning of panels.
- Level surface of floor panels.
- Plumb alignment of wall panels.
- Level alignment of ceiling panels.
- Correct maximum gaps between panels.
- Proprietary fixings correctly installed.
- Workmanship

It is anticipated that the following data will be gathered from the above experiment from two categories of crews:

- Experience level of the workers.
- Experience level of the inspectors.
- Education/ qualification level of the inspectors & workers.
- Errors detected (according to survey made by an independent experienced inspector).
- Errors undetected (as above).
- Total time taken for inspection.
- Total time taken to construct the cabin.

The data collected will be examined with reference to probability concepts described for engineering planning (Ang and Tang, 1984).

The construction industry is likely to experience an explosive growth in the use of 3D and 4D CAD documentation in the next ten years. This research proposal aims to verify the effectiveness of such documentation as a means of reducing errors and therefore improving efficiency. It will also examine the attitudes of a section of the construction workforce to such forms of documentation and their readiness to accept change.

4. CONCLUSION

When compared to the manufacturing sector the construction industry worldwide has been slow to adopt the potential benefits that are afforded by new technologies based around 3D and 4D CAD. This has been due to a combination of attitudinal reluctance for change and technical difficulties in making the computer models reflect the complexity of the construction process. Nevertheless, computerisation of the construction industry is inevitable as a new generation of workers emerge with greater familiarity with Information Technology from their schooling. The ongoing research described in this paper is part of an effort to understand and quantify the consequences of the coming changes. The potential benefits from the adoption of innovative technology in documentation are enormous. They offer the possibility of a reversal of the trend towards diminishing construction documentation quality. Properly implemented 3D and 4D CAD systems can improve communication of the construction process and therefore close the proverbial gap between the idea and the implementation.

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