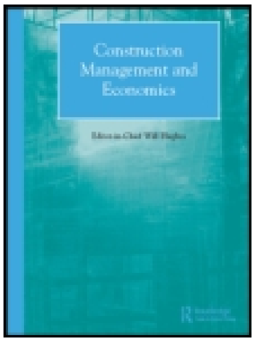

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Trends of 4D CAD applications for construction planning

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Since the early 1990s, there has been a growing interest in four-dimensional computer aided design (4D CAD) for construction project planning. Commercial 4D CAD applications are becoming more accessible and the use of this technology allows the construction planner to produce more rigorous schedules. A review of the technical competencies of these packages highlights that most of the commercially available packages concentrate on the use of 4D CAD simulations for aesthetic visualization purposes. Very few packages offer the ability to carry out analytical tasks on the developed simulation and this is often left to the interpretation of the user. A thorough appraisal of emerging research developments in 4D planning highlights that this technology is employed for various applications; however, the amount of detail required in a 4D simulation is still ambiguous. A model is proposed to determine the attributes required for use with each of the various applications of 4D CAD simulations. Finally, various lines of future research are highlighted, including the need for improved use of data exchange standards and the automation of linking the construction tasks to the 3D CAD model.

Keywords: Visualization, construction planning, simulation, four-dimensional CAD

Background

Effective planning is one of the most important aspects of a construction project and influences the success of a project (Chevallier and Russell, 1998). Fischer (2002) argued that there are fundamental differences between a construction plan and a construction schedule. Whilst a plan shows activities and their logic relationships, activities do not show specific start and end dates. A schedule shows temporal information, which enables project duration to be defined.

Developing the construction plan is a critical task in the management of a construction project (Hendrickson, 2000). Illingworth (2000) stressed that effective plan generation requires competent and experienced personnel. However, emerging evidence suggested that there is a shortage of skills in the area of construction planning, with the number of experienced planners having the knowledge or ability to effectively plan construction projects, decreasing (Kelsey *et al*., 2001). In addition, it was found that experienced project managers actually have remarkably little time to plan on most construction projects (Kelsey *et al*., 2001).

It is commonly acknowledged that the scheduling of construction activities is only a section of the entire construction planning process. During the formulation of a complete construction schedule, planners and site managers are required to simulate various construction processes, required to build the project. This simulation can either be done intuitively by the planner or by using a computer based simulation techniques, such as discrete event simulations methodologies (Halpin and Riggs, 1992). Computer-based decision support tools have provided the construction planner with the ability to plan construction tasks efficiently using techniques such as Critical Path Method (CPM) and Critical Chain. The building block of these methodologies is the construction task, which concentrates mainly on the temporal aspect of construction planning.

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In addition, these methodologies allow for resources to be taken into account. However, the heavy reliance on these methods leads to the planning process being seen as one-dimensional (i.e. taking into account the time aspect).

Recently, Winch (2002) emphasized that certain planning decisions, especially those associated with spatial planning, are made on the basis of experience and intuition, without the support of tools such as those available for the sequencing of tasks (i.e. critical path analysis and its derivatives). Emerging research efforts are currently focused in the provision of project planners and managers with computer-based advisory tools to visualize the construction plan in a 4-dimensional (3D computer model + time) environment.

Hendrickson (2000) discusses the concept that construction plans usually have an emphasis either on cost control or on schedule control. The use of procedures such as CPM scheduling, concentrate on the task duration and precedence's whilst the resource information is used to develop the temporal aspect of the task. The use of 4D planning is considered to correspond to this area of the construction planning process as it provides greater assistance in the temporal/scheduling genre (see Figure 1).

Although 4D CAD in the construction industry has been developing since 1987 (Fischer and Kam, 2001), the interest in this area has grown rapidly in recent years. Barrett (2000) perceived this technological development as having the potential to provide an improved relationship between construction designers and constructors. 4D CAD was seen as a natural progression to 3D CAD models, as it adds a further dimension (Phair, 2000). It provides the ability to represent construction plans graphically (Williams, 1996), by adding the temporal dimension to

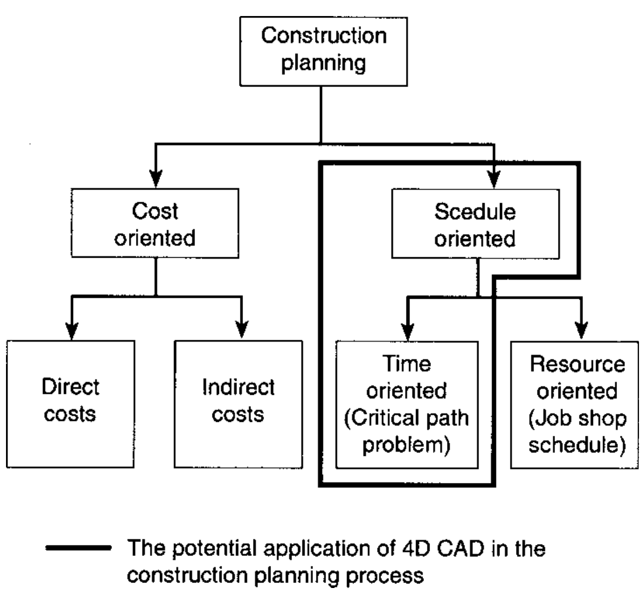

Figure 1 The construction planning process (adapted from Hendrickson, 2000)

3D CAD models, i.e. linking a 3D graphical model to a construction schedule, through a third party application (Collier and Fischer, 1996; McKinney *et al.*, 1996). In addition, Kutsson (2000) perceived 4D simulation as a 3D interface to the construction process model, whilst Koo and Fischer (2000) highlight its ability to visualize progress of the construction phase, by linking units of work to the work tasks on the construction schedule.

Work carried out by Coles and Reinschmidt (1994) demonstrated that creating a 3D model over time assisted in the planning process. Webb (2000) envisaged that the use of 4D simulations could assist in halving the waste costs associated with a construction project. This technology has the potential for presenting ideas to clients in order to promote collaborative working (Fischer, 2001; Kahkonen and Leinonen, 2001a), and to assist in the problems associated with site logistics and site layout (Zhang *et al.*, 2000). Moreover, it can be used to improve site logistics, such as work execution space (Akinci *et al.*, 2000a; Heesom and Mahdjoubi, 2002) and to analyse the construction schedule to assess its executability (Koo and Fischer, 2000). Additionally 4D simulation has proven useful as a medium for the evaluation of alternative construction schedules (Vaugn, 1996) and even as a training tool for inexperienced planners (Jaafari, 2001).

The purpose of this paper is to provide an overview of current and emerging trends in the development of 4D simulation, which have affected or likely to have an impact on construction project planning. First, it seeks to examine prevailing software developments in 4D planning to evaluate the potential and limitations for construction project planning practice. Secondly, it proposes to analyse the rationale for emerging research initiatives in this field. Their fundamental concepts, methods, techniques and applications are examined. Based on this analysis, salient research issues are identified and future lines of enquiry are suggested.

Commercial 4D software

With the emergence of 4D CAD as a tool to assist the comprehension of construction project plans, various software packages have been developed, however most of these concentrate on the utilization of 4D CAD as a visualization tool, rather than something that can be used for analytical purposes. The following sections present a technical review of existing 4D visualization software packages. A technical comparison of currently available 4D simulation software can be seen in Table 1.

Schedule Simulator – Bentley Systems

The Bentley Schedule Simulator emerged from the PlantSpace Schedule Simulator initially developed by

Table 1 Technical comparison of commercial 4D software

Name	Add into existing CAD package	Stand-alone package	Manual linking of product process	Formalized PBS-WBS linking	Type of CAD data required	IFC compliant	Planning software supported	Visualization medium	Web enabled	Real time updates of task 3D model	3D product object grouping	Real time navigation of 3D environment
Bentley Schedule Simulator	No	Yes	Yes	No	Microstation	No	Primavera	Internal Bentley 3D Format	No	No	Manual	No
Common Point 4D	No	Yes	Yes	No	AutoCAD, VRML	Yes	MS Project Primavera	VRML, 3D Studio, Macromedia Shockwave, AutoCAD dwg format	No	Yes	Manual	Yes
SmartPlant Review	No	Yes	Yes	No	VR 3D objects (VRML)	No	MS Project Primavera	Internal 3D Format	No	Yes	Manual	No
Project Navigator	No - Add in to Web Browser	Yes	Yes	No	3D VR Objects (VRML)	No	None	VRML	Yes	No	Manual	Yes
FourDviz	No	Yes	Yes	No	3D CAD data (DXF)	No	None	Internal 3D Format	No	Yes	Manual	Yes
Visual Project Scheduler	No	Yes	Yes	No	DXF	No	None	OpenGL	No	No	Manual	Yes

Jacobus Technology. The schedule simulator uses the Bentley Enterprise Navigator 3D environment to perform 3D graphic simulations of the construction process. Raw 3D design data can be imported from various CAD based design packages. The schedule data can be obtained from either Primavera Project Planner or Microsoft Project. To incorporate data from these packages, the system utilized OLE2 (object linking and embedding) Automation, dynamically linking schedule data. With this system, any amendments made to the schedule in P3 or Project can immediately be visualized in the 4D environment. In addition, the system also provides the option to use Open Database Connectivity (ODBC) to import schedule and CAD information.

Once the CAD and schedule information is imported, CAD objects can be associated to schedule activities and animations are generated. This link between the tasks and the 3D objects is carried out manually, using various relationships, including one-to-one, one-to-many or many-to-many.

SmartPlant Review – Intergraph Incorporated

The construction module of the SmartPlant review contains ScheduleReview. This is an engine that allows 4D simulations to be generated by linking information from the project schedule to objects in the CAD display. The 3D objects for the simulation are generated and shown using the SmartPlant Review engine. Whilst this provides the visual elements, the temporal information can be imported and used through either Primavera Project Planner or Microsoft Project. Using Primavera Project Planner, OLE technology can be utilized for updating temporal activity information, which enabled the updated information to be directly related and visualized in the 4D simulation

Groups of 3D CAD model elements can be defined either automatically or manually and these can then be associated with activities defined in the imported project schedule. Once associated, the objects can be user defined according to their status during the simulation. For example objects not yet constructed can be displayed as wireframe, whilst completed objects can be shaded.

Project Navigator 2000 – VirtualSTEP

The software is a browser-based application, providing the ability to dynamically link schedule information and AutoCAD based drawing objects, to present a simulation of construction schedules. The software utilizes a central control panel, as an addition to the standard Internet Explorer browser. Schedule and CAD information can be entered and the critical path of the schedule can be analysed using a CPM engine. In addition, the user has the ability to input resources and costs to monitor these as the project progresses.

FourDviz – BALFOUR Technologies LLC/Infinity Technologies

Within FourDviz, virtual reality objects can be generated to create the visual scene. This provides a real time environment that can be navigated by the user, allowing movement through any part of the virtual construction site. In addition to the 3D creation of the objects, temporal characteristics can also be attributed. Once a date was attributed manually to each of the objects in the 3D world, a simulation is compiled for the duration of a specified period.

The temporal characteristics of 3D objects are assigned as particular dates or days, and as such, no analysis is made of the schedule compiled. FourDviz does not contain a scheduling engine or the ability to calculate critical path analysis of schedules. Therefore, this calculation has to be carried out before dates are associated to objects. In addition, there are no dynamic links between a CPM based package and the visualization.

Common Point 4D

Common Point 4D is a tool that has emerged from the research activities undertaken at the Centre for Integrated Facility Engineering (CIFE) at Stanford University, USA. This tool uses 3D IFC compliant models that can be generated from AutoCAD dwg or DXF formats. Schedule information is read from Primavera or Microsoft Project file formats. The linking of products to processes is undertaken manually using Product Based Schedules (PBS) to Work Based Schedules (WBS) linker tool.

The transparency of objects in the simulation can be varied to show various product groups, and objects can be manually grouped together and attached to one or multiple tasks. The time scale of the simulation can be varied to provide a level of detail. Furthermore, annotations can be added to each 4D product group to provide an explanation of the 3D objects during the simulation. Tasks can be edited in the 4D software in order to provide alternative scenarios.

Visual Project Scheduler

Visual Project Scheduler (VPS) can import various 3D DXF files into a common database so that objects can be reviewed. Objects in the overall model can then be broken into parts and regrouped as construction objects. The colour of objects, or parts of those objects, can be changed to display specific meanings. Using an 'activity wizard', activities can be generated automatically for all 3D objects in the model, by selecting objects in the sequence of construction. Whenever an object is assigned a construction class, the number of labourers and a calculated duration will be automatically allocated.

VPS can import activities and relationships from external databases. These activities can then be graphically associated to objects in a model. VPS utilizes an OpenGL rendering interface to display models as solid or wire frame images. Using a control panel, the user can move in and around the model whilst, snap shots can be generated and saved as files. A built-in AVI generator can create video files of the output, including the path taken around the model.

Furthermore, several research institutions have developed prototype applications to assist in a specific utilization of 4D CAD. Such examples include the CIFE 4D simulator (McKinney *et al.*, 1998), the GALLICON project (Sun *et al.*, 2000), OSCON (Aouad *et al.*, 1997), DIVERCITY (Kahkonen and Leinonen, 2001b) and the VR Planner (Retik and Shapira, 1999). A technical evaluation and comparison of these prototype systems can be found in Dawood *et al.* (2003b).

Emerging research initiatives

The following section provides an overview of emerging research initiatives in 4D planning. Overall, three broad research areas were identified, according to their particular areas of application:

- product modelling and visualization;
- process modelling and analysis; and
- collaboration and communication.

Product modelling and visualization

A considerable amount of literature proposes that 4D CAD technology has provided useful tools for product modelling and visualization. The improvement in data exchange, including the use of neutral data exchange formats – for example, Industry Foundation Classes (IFCs) (Liebech and Wix, 1999) – is greatly enhancing both the time and the accuracy of the creation of product models. Work currently being undertaken at VTT in Finland has demonstrated the potential of IFCs to aid 4D modelling, whilst CSTB (France) are generating software tools to allow the direct conversion of IFC data into 3D VRML models.

Currently, 4D CAD is extensively used as an explanative and communication tool. Liston *et al.* (2001) reported that 4D CAD is commonly used during meetings to explain designs and describe work packages. This study demonstrated that when 4D CAD is used in construction project meetings, approximately 50% of the time is spent using the model to explanative designs whilst a further 20% is used to assist in describing construction operations (Liston *et al.*, 2001). The utilization of 4D visualization allows a more intuitive comprehension of the construction process than traditional 2D drawings and schedule information (Bergsten, 2001).

Several efforts sought to incorporate construction planning and Computer Aided Design (CAD) data. Cherneff *et al.* (1991) integrated CAD data with construction schedules. Using the 'Builder' system, a knowledge base extracted geometric product information from CAD drawings, and generated activities for each product. Retik (1993) proposed a real time 3D computer graphics system to allow the visualization of product data at different stages during the construction process. This system allowed the visualization of the construction process over time.

Collier and Fischer (1996) opted for commercially available software packages such as AutoCAD and Primavera to generate 4D simulations. These tools were used for communication and dissemination of information to both clients and contractors. The software was tested in live projects such as the San Mateo Health Centre (USA) and Walt Disney Concert Hall. Using these simulation tools, details of the progress of the project could be communicated effectively to Walt Disney's directors (Goldstein, 2001a).

Other important uses of 4D visualizations have, so far, been in the marketing and pre-construction phase of a project. For instance, during the construction of the Lynchburg General Hospital, Virginia, Bovis USA used 4D simulations to demonstrate construction work sequencing (Webb, 2000). 4D CAD simulation provided a medium for various parties involved in the construction project to understand the sequence of construction and progress made at specific points in time.

The representation of the construction project at various time intervals was refined further using virtual reality (VR) technology. A 'VR Planner' was developed to allow the evaluation of alternative strategies during the planning process (Retik, 1996). This system enabled the viewing of the construction product model, at discrete weeks within the construction schedule, in a real-time environment. An intelligent interface was added to the VR Planner, which used a knowledge base to assist in the representation of construction activities (Retik and Shapira, 1999). Other efforts sought to generate a library of virtual reality objects to represent various building components, including facilities and temporary works (Adjei-Kumi, 1997).

Further work was carried out to take advantage of advances in real-time technologies by (Kähkönen and Leinonen, 2001a). Software was developed to enable the representation of construction progress using a Virtual Reality Modelling Language (VRML) interface. The 4D browser links IFC-based 3D product model data to schedule data, through a web interface (Kähkönen and Leinonen, 2001b).

Process modelling and analysis

Although a large effort in 4D simulation research has aimed at developing explanative and descriptive tools, recent trends have involved the use of this emerging technology for analysis and predication (Liston *et al.*, 2001). 4D planning provides a new opportunity for the representation of construction scheduling, which could advance the principles of planning, past the Gantt chart (Richmoller *et al.*, 2001) and could allow the analysis of construction schedules prior to the construction phase. For instance, the 'Gallicon' project undertaken at Salford University, UK, utilized virtual reality simulation to depict the products that are under construction at a specific point during the construction process (Sun *et al.*, 2000).

The integrated design, cost, and schedule model records and communicates the status of the construction process (Fischer *et al.*, 1999). 4D Simulation technology has been employed to assist in the area of cost control and estimation. Staub *et al.* (1998) reported that 4D simulations were linked to cost estimating software tools for automated quantity takeoff. This work explored the usefulness and limitations of commercial software tools to support integrated design-cost-schedule management from conceptual design to construction, in a multi-company environment. The project concluded that by explicitly modelling the relationships between design, cost and schedule information, construction planners and managers can automatically disseminate design and planning changes, whilst ensuring that the project's design, cost estimate, and construction schedule are aligned. Additional work has linked 4D information to the cost schedules to obtain automated cost breakdowns. For instance, O'Brien (2000) suggested that '5D CAD' should include the cost element of the construction process. The cost benefit analysis of using 4D models in both the construction planning and control phase have been highlighted by Fischer (2001). As shown in Figure 2, through using 4D simulations the cost incurred to a project through unplanned changes is dramatically reduced.

In order to facilitate more widespread use of 4D models for modelling the construction process and analysing construction sequences, improvements need to be made in the creation stages. Currently, 4D models are generated by a combination of planners and 3D modelling experts. The construction planner provides a schedule of activities whilst the 3D modelling expert provides a 3D model. A third party would then be responsible for the linking of the tasks on the construction plan to the 3D elements of the model. Work undertaken by Dawood *et al.* (2003a) has proposed the use of the Unified Classification System (UNICLASS) to semi automate this process (Figure 3). UNICLASS provides codes to represent both the Product Breakdown Structure (PBS) and the Work Breakdown Structure (WBS) for a building project. The planner could generate these two codes, thus allowing a semi automated linking of the schedule and the 3D model and hence easier creation of a 4D model.

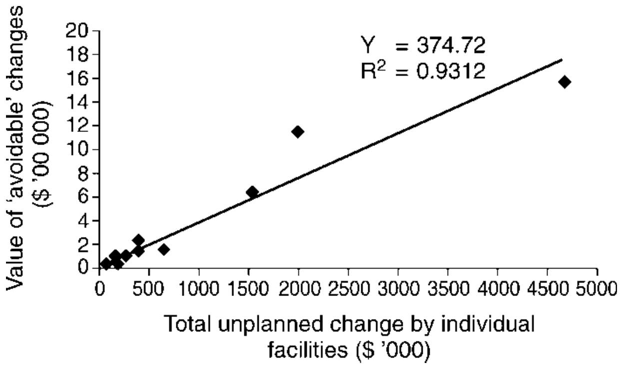

Figure 2 Value of unplanned changes using 4D simulations (source: adapted from Fischer, 2001)

In order to improve the analytical power of 4D CAD, the simulations are being linked with other technologies used by the construction industry. Moore (2002) discussed the incorporation of 4D technology into the area of Geographical Information Systems (GIS). This work presented a case study of the use of GIS to the design of a stadium facility, allowing topological queries to be generated with the inclusion of a temporal aspect.

One of the main advantages of using 4D CAD for process modelling is the ability to analyse various construction schedules and assess their logic. Songer (1997) highlighted the advantages of using such simulations for analysing schedule logic. Additionally, work undertaken by Koo *et al.* (1998) demonstrated that 4D could assist the identification of problems that would normally be overlooked in a traditional schedule representation, such as bar charts and network formats. Using 4D technology allowed relatively inexperienced construction professionals to identify problems that can be neglected by experienced personnel in the traditional schedule formats. This analytical capability has been further exploited by allowing construction-planning students to visualize and analyse a complete construction schedule prior to construction to assess the suitability of a construction plan (Koo and Fischer, 2000; Jaafari *et al.*, 2001).

4D simulations can also be used as an analysis tool to assist the planning of space usage on the construction site, a process that is known to be an arduous task (Kelsey *et al.*, 2001). The planning and analysis of space usage on the construction site was the focal point of numerous research efforts (Riley, 1994, 1998; Thabet and Beliveau, 1994). Some researchers advocated the use of 4D simulations to assist in detecting potential time-space conflicts that may occur between activities being executed on a construction site (Akinci *et al.* 2000b). Systems developed to deal with this issue, sought to generate workspaces, which were then included into a 4D model to detect time space conflicts. A collaborative project in the UK (The Virtual Construction Site – VIRCON) has investigated the development of Critical Space Analysis tools to enable a space-based analysis of construction operations (North and Winch, 2002). This project has utilized a developed 4D interface to view the results of the analysis and preview critical spaces (Heesom and Mahdjoubi, 2002; Dawood *et al.*, 2003b).

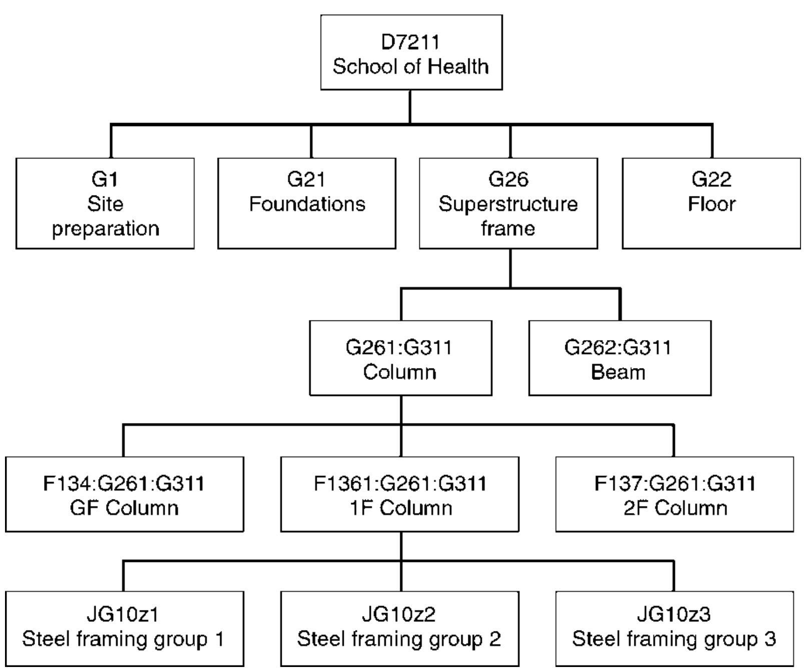

Figure 3 Formalizing 4D PBS-WBS using UNICLASS (Dawood *et al.*, 2003)

Specialist trades are often the source of temporal delays in construction schedules, with 'knock-on' effects to other allied activities. The sequencing of various trades in the construction project is an area where 4D CAD can assist planners and site mangers in the decision-making process. Heesom and Mahdjoubi (2003) investigated the use of 4D CAD simulations to analyse the sequence and areas used by mechanical, electrical and groundwork trade operations. This work developed interactive tools to allow the planners involved with various trades within a construction project to view the work in 4D and then interactively assign the workspaces required. The project also developed animated route paths for spatial analysis. Once the workspaces are assigned they can be viewed and analysed in a real time 4D simulations environment. This allows the construction planning team to view space usage on the site a various stages throughout the project.

Although 4D CAD has mainly been used for detailed simulation of the construction process, the technology lends itself to assisting in the site layout paradigm. Site layout planning and the optimisation of site logistics have also attracted great deal of attention (Tommelein, 1995; Yang and Mahdjoubi, 1999; Zouein and Tommelein, 2001). Work undertaken by Zhang *et al.* (2000) led to the development of a 4D site management tool, '4D Graphics for Construction Planning and Site Utilization' (4D-GCPSU). This system provided the planner with a more robust 4D representation of the site layout plan, which included materials.

Akbas *et al.* (2001) proposed the use of 4D CAD to analyse the 'zones' or areas used by construction operations during various stages of the construction process. This information is then utilized to plan activities that take place in various locations on the site. McKinney and Fischer (1997) reported the use of 4D production models, to provide the ability to check and analyse temporary support objects required throughout the construction process.

Collaboration and communication

Allowing 4D simulations to be generated and viewed in a collaborative environment will assist the collaborative construction process. Due to the fragmented nature of the construction industry (Issa, 1999), numerous contractors and subcontractors can be working on a construction site during any stage. A 4D model can assist in the communication between different contractors to best determine execution patterns and avoid conflicts between trades. The use of 4D CAD for collaboration and communication has received a great deal of attention. McKinney and Fischer (1998) described the current process of project planning as utilizing a 'mental 4D model', depicting the mental association made between the 3D building products and the schedule of activities. The use of mental 4D models allows ambiguity between the visual representations of the construction project and can lead to problems of communication and collaboration between the various parties involved in a project, including the client, the contractor and the sub contractors. Each party receives project information including a project schedule, 2D drawings and 3D product model and from this builds a mental 4D model of how the building will be built. It is often these are not the same, which leads to communication difficulties. An actual 4D model can remove these discrepancies and allow all parties to communicate using the same model.

Early 4D systems were criticized for their lack of functionality to visually communicate non-descriptive information; i.e. the reasons for activities to be scheduled in a certain way (McKinney and Fischer, 1998). To resolve this key issue, research was undertaken to generate 4D models that are more 'explanative and predictive'. The main thrust of work in this area sought to add annotations to 4D models that visually explained potential construction problems to planners, making the model more accessible in supporting decision-making. The annotations could also be used to highlight how the construction sequence affected other factors relating to the project, i.e. cost (McKinney *et al.*, 1998). As a result, a mechanism was developed to associate the content of the annotation with the 3D component of the building. McKinney *et al.* (1998) developed a modular system to allow annotations to be added to the simulation. An initial module allowed planning features, such as the requirement of the component to be supported by another component, which outputted a 4D model with planning features. The model could then be used as an input into a planning system, requiring knowledge of component relationships. The second module provided a graphic environment for the user to view various types of planning information.

An application of 4D to assist collaboration was carried out by the Centre for Integrated Facilities Engineering (CIFE) at Stanford University and Walt Disney Imagineering (WDI). Using a 4D prototype tool, the construction of the Paradise Pier portion of Disney's California Adventure was planned. The research group also used the 4D tool on the Frank Gehry designed Disney Concert Hall in Los Angeles to help co-ordinate subcontractors, study the constructability of the design, and verify the executability of the construction schedule (Goldstein, 2001b). 4D modelling was also used extensively for the simulation of the Logan International airport modernization project. In this example, 4D simulations communicated crucial information to airport planning bodies, as it enabled the progress of work on the airport to be visualized at discrete points, in a way that a 3D model of the final project could not provide (Edwards and Zeng, 1997).

The collaboration between clients and designers was identified as one of the main problematic areas for the industry. Rad and Khosrowshahi (1997) stressed that although 3D visualizations have gone some way to closing the communication gap between clients and designers, 4D CAD is allowing this communication gap to narrow even further. The authors discussed the use of 4D simulations, through a virtual reality interface, to allow the visualization of building maintenance schedules, assisting collaboration between the parties involved. Frolich *et al.* (1997) examined the use of an interactive workbench that allows 3D CAD models to be assembled and disassembled, in a 4D environment. The system allowed the parties involved in the planning process to manipulate 3D graphical objects relating to the construction schedule in an immersive environment.

It is anticipated that by 2005 between 20 and 50 per cent of the construction industry's workload will be carried out using the Internet (Mylius, 2000) and with the increased use of the World Wide Web, 4D product models could be shared through this medium to further assist communication and collaborative working practices.

Discussion

The exploration of current and emerging body of work in 4D planning has led to the identification of the following salient research issues: information flow, level of representation and dynamic simulation. A review of research in 4D CAD demonstrated that information flow is one of the most critical issues in the development of tools in this field. Research has shown that the use of data exchange standards, such as IFCs, have, to a certain extent, improved information modelling and exchange between various applications in 4D planning. However, most of this research is still at its infancy. As a result, manual data input still prevails in the industry. For instance, although some research initiatives have attempted to introduce a certain level of automation in data exchange, most applications still require some manual input between CAD and databases or databases and schedule information. This labour intensive activity could be considered as a potential reason for the slow uptake of 4D simulations by the construction industry. It was proposed by Kim and Gibson (2003) that one of the main reasons for the low take up of new prototype computer systems in the construction industry was due to their complexity. Therefore, in order to facilitate more widespread diffusion of 4D simulations in the construction industry, 4D systems should be easy to use and require a minimum level of input, allowing the planner to understand and quickly use the tools with a minimal lead in time.

The level of interactivity required with the 4D simulation is critical for project planning tasks. The use of 4D simulations for product modelling and visualization can help with marketing or client briefings. For activities of this nature, interacting with the model, for example making on the fly amendments to the simulation or obtaining data through querying objects within the simulation, may not always be required. In many cases, an animation is sufficient. However, if the model were to be used for analysis of the construction process, then a higher degree of interactivity would be required. For example, the planning team may wish to investigate various construction methods in order to determine the best construction sequence. The testing of these sequences requires a high level of interactivity, whereby changes to the schedule can be viewed immediately in the 4D model and their implications can be analysed.

Another important issue that arose from the review of 4D CAD is the visual representation of the simulation. There are three main issues surrounding the visual representation namely information content, the level of detail of the 4D simulation, and the dynamic capabilities of the simulation.

For product modelling the graphical representation of the 4D model is commonly shown at a high level. Reviews have shown this type of 4D simulation is used extensively as a marketing or demonstration tool for clients. This type of simulation could show a very detailed geometric representation of the 3D product model, leading to a photo-realistic representation. The converse situation is true for other applications of 4D CAD simulations. For example, 4D simulations used for process modelling and analysis do not require high-level graphical representations. These may only be required to allow 'quick and dirty' scenarios to be viewed for specific purposes. Consequently, 3D products could be displayed, as simplified 3D primitive shapes.

Fischer (2001) suggested that the level of detail of the simulation relates to the level of detail of the construction schedule developed by the planner, which is in turn relates to the breakdown of the products in the 3D model. For example, some planners may plan at the bar chart level. Tasks generated, at this level, may relate to a large group of products in the 3D model, displaying a 4D simulation at a low level of detail. Others may use a full work breakdown structure (WBS), which can be linked to individual products in the 3D model, showing a 4D simulation with a higher level of detail. Tailoring the simulation to meet these specific needs assists the comprehension of 4D models.

The detail of the construction schedule and the level of the 3D model used can have implications on the time spent on creating the 4D model. 4D simulations developed for various applications require differing levels of detail. For product modelling and visualization, it may not be important to have a high level of detail in the schedule, as the simulation is commonly used only as a visualization medium. It could be used to aid the construction team in conveying the construction process of the overall design to lay people. However if a model is utilized for process modelling or analysis, a higher level of detail within the schedule is often required. During the analysis phase, the construction team will require to see as much detail as possible to ensure that informed decisions are made. This enables the analysis of various aspects, such as schedule logic, clash detection between building products and site logistic analysis. Another factor, which will have an effect on the level of detail, is the time interval within the simulation. For product modelling, it may be useful to see the model evolve at weekly intervals, however, for analysis of site space a daily interval may be required (Table 2).

The dynamic capability of the 4D simulation is also a significant factor in 4D planning research. Generally within 4D simulations, 3D objects appear at discrete points throughout the duration of the associated task (i.e. the start or end of the task or at some point in between). Some commercial 4D packages allow limited manipulation of objects so that they are highlighted during the task time period. However, by using this method, the entire product is displayed for the whole task duration, which is not representative of the construction process. Some methods advocate the manual grouping of 3D objects to overcome this problem. Recent efforts have been devoted to solving the problem of creating more dynamic 4D simulations by formalizing construction zones, displaying 3D product data, according to the zone specified or using construction strategies to develop more dynamic product geometry based on semi-automated algorithms. The use of more dynamic simulations is particularly useful when 4D models are required for analytical purposes. It provides the planning team with a more realistic picture of how the construction site will evolve. In addition, 4D simulations have huge potentials for spatial planning analysis. For instance, the inclusion of dynamic route paths throughout the duration of a construction project can be beneficial to workspace analysis. This type of analysis could account for space usage and requirements by personnel and materials movements. Except for few initiatives (e.g. VIRCON project), this area of research has been neglected, and therefore, require further attention.

Conclusions

The use of 4D CAD has significant potential for the construction industry. 4D simulations can have a positive impact on both pre-construction and the construction phases, whilst having the power to assist planners in producing improved planned projects, allowing them to see how their plan will evolve.

In addition, 4D technology enables planners to predict potential problems at the construction stage, which could have considerable costs and time implications. Where 4D technology has been embraced, direct savings and an increase in productivity has been seen. The use of 4D CAD simulations allows considerable savings to be made on construction projects by identifying problems prior to construction and avoiding re-work during the project.

The fundamental attributes required by 4D models vary depending on construction project planning practice. Whilst the use and application of this technology is increasing, the following lines of research require further investigation:

- improved detail differentiation for graphical representation;
- improved use of data exchange standards;
- the inclusion of dynamic work execution spaces in 4D simulations to allow a more comprehensive analysis;
- more automated techniques of linking the construction tasks to the 3D model; and
- advancing the use of 4D principles to incorporate other construction / built environment software tools, for example GIS, cost estimation and health and safety.

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Table 2 Fundamental requirements for 4D simulation applications

Application	Attributes			
	Level of interactivity with 4D simulation	Level of graphical representation	Level of interactivity with 4D simulation	Level of dynamic capability of simulation
Product modelling and visualization	Low	High	Low	Low
Process modelling and analysis	High	Low	High	High
Collaboration and communication	High	Low	High	High/Low

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