The Virtual Construction Site (VIRCON): A Decision Support System for Construction Planning

Nash Dawood, Brian Hobbs, Abi Akinsola, Zaki Mallasi
School of Science and Technology, University of Teesside, Middlesbrough TS1 3BA, UK

Lamine Mahdjoubi, David Heesom
School of Engineering and the Built Environment, Wulfruna Street, University of Wolverhampton, Wolverhampton, WV1 1SB, UK

Graham Winch, Alan Penn, John Kelsey, Andrew Edkins, Steve North*
Bartlett School of Graduate Studies, UCL, Gower Street, London, WC1E 6BT, UK

Abstract. The research proposed here is the subject of a substantial research grant from EPSRC (IMI/CMP) and aims to develop a prototype application for evaluation, visualisation and optimisation of construction schedules within a virtual realty interface, called *The Virtual Construction Site* (VIRCON).
The building block of construction planning methodology is the task. The array of tasks provides the work breakdown structure; the temporal sequencing of tasks is the core of CPA; and the resourcing of tasks provides the input costs of the works. However, what is usually ignored in current methodologies is the fact that task execution occupies space on site, and spaces occupied by one task are often not available either for the execution of other tasks, or the movement of resources between different task execution space. Spatial domain is critical to construction projects and at present the spatial dimension is treated intuitively by experienced planners. VR techniques offer considerable potential for visualising and analysing the spatial and temporal distribution of tasks to inform the decision making process. In this context, the ultimate aim of the project is to provide a desktop strategic decision support tool which will allow planners to trade off the temporal sequencing of task with their spatial distribution. The result would be a more robust and rehearsed project schedule.
The paper outlines progress to-date and future developments of the VIRCON project.

KEYWORDS: Construction Planning, Simulation, Space analysis, VR.

1. Introduction

Construction planning is the process of defining and identifying construction tasks, their dependency and resources needed to deliver a construction project. As construction projects are unique, a perfect plan of a construction project is often achieved after the project is finally completed and delivered. *New Civil Engineer* (5/11/98) reported that the construction industry "practised on its customers' time and money." It is apparent that the need for rehearsing processes before construction starts is important to meeting Egan targets. The proposed research will build on work by the collaborators and elsewhere which has advanced the visualisation of task sequences beyond the Gantt chart, while adding a new dimension to construction planning, that of *critical space analysis*. The aim will be to provide a tool which will allow planners to trade off the temporal sequencing of tasks with their spatial distribution. The result will be a more robust and rehearsed project schedule. It has been developed in response to the realisation that there is a looming skills gap in the construction industry amongst those with the expertise to plan major construction projects, and that there are a range of technical opportunities becoming available which may make it possible to bring computing to bear on what has until now been a task that is only tractable by experienced and expert personnel. Thus the research proposed here aims to develop a prototype application for evaluation, visualisation and optimisation of construction schedules within a virtual realty interface, called *The Virtual Construction Site* (VIRCON).

The UK construction industry has been experiencing fundamental changes in delivering medium and large size construction projects. It has moved from main contracting to construction management, and now most medium and large-scale projects are procured in this way. This has had two main effects:

1) The proliferation of separate subcontractors for almost every item of work can itself lead to inefficiencies and conflicts on site. Work is often repeated leading to damage and wasted effort. Access often becomes the responsibility of each individual trade contractor, and this can lead to inefficiencies in provision and difficulties in ensuring compliance with regulations. Recent research at UCL on the application of CDM (Nutt *et al* 1998) suggests that 20% of reported construction accidents can be attributed to poor site logistics. In a separate study of productivity analysis of £6 Million University building by Malasi, Dawood and Winch, it was concluded that low productivity is highly correlated to inefficient space planning and conflicts between sub-contractors. This study is discussed further in this paper under Development to-date section.
2) There is increasing concern over an emerging skill gap in the industry as the last cohort of project managers and construction planners with main contracting experience approach retirement. The problem is that the younger staff have no experience of the whole range of operations which take place on site, and the industry structure is no longer able to give them that experience.

Dealing with the programming and management of activities on site and the proliferating numbers of trade contractors has therefore become of critical concern just as the staff with appropriate experience and skills are becoming scarce. New forms of procurement such as public private partnerships and design/build/ finance/operate are compounding the issue by shifting the appreciation of risk for satisfactory operation and maintenance to the construction industry, and allowing contractors a greater say in design and construction methods. Significantly more intelligence needs to be brought to bear in the planning of the construction process if the targets set by the Construction Task Force (1998) are to be met. The problem is that construction programming and management are immensely difficult and complex tasks, in which spatial and temporal decisions must be made at strategic, tactical and operational levels. The combinatorial complexity of possible programmes for the construction of even the simplest of buildings is uncountable, and when other factors are introduced including human and organisational issues and regulatory or safety considerations, considerable sophistication and judgement in project planning is required. The research proposed here will develop a possible solution to some of these issues.

2. Previous Studies

It is intended to learn from the manufacturing experience - the results of the application of VR to various sectors of engineering have so far been tremendous (Boyd 1998; Wilson 1996). VM has been shown to avoid costly mistakes, and enable planners and managers to envision the whole manufacturing process from design and assembly to product shipping. Factory simulation has helped to make substantial savings on tooling, design, construction and installation. Compared to the use of conventional methods, VM has also been shown to dramatically reduce the amount of time it takes to analyse new design concepts and incorporate them into the production process. It has enabled decision-makers to make last minute changes and eliminated the need to build prototypes. The application of VR has made it much easier for factory workers to accomplish complex and error-prone tasks, and has also offered a safer environment for testing various manufacturing techniques.

Some of the approaches and principles developed for an engineering context may find construction applications, for instance for the visualisation of building layouts (Bridgewater and Griffin, 1994). However, construction sites vary in terms of their size and complexity and are therefore inherently different to manufacturing processes. In particular whilst for manufacturing it is possible to optimise a process within the controlled environment of the factory, in construction the product and the environment used to create that product occupy the same space. As the building is built it constrains the space available to construct later phases. In essence, in construction, site processes are continually constrained by the changing form of the building as it is built, and by the effects of current tasks in occupying space and denying access to other areas. This makes construction scheduling a much more complex operation than that encountered in most manufacturing processes.

There are a number of methodologies/systems being developed in the UK and USA to tackle this problem (see Mackinney and Fisher 1996; Pierrette Zouein 1995; Hendrickson 1997; Soh et al 1993; Tommelein et al 1992; Williams 1996 and work within the VRCBE). These methodologies/systems were developed to facilitate automatic production of construction schedules from 2D or 3D drawings. All of these systems use heuristic/knowledge rules encapsulated in a prototype computer model. A major drawback of the systems developed so far is the lack of practical applicability to the construction process. One approach has been to develop the use of object technologies and VR interfaces to aid in the communications aspects of construction projects (Penn et al, 1995, 1996). The approaches have been applied to construction site processes by Williams, 1996 and Retik 1996 who have developed 4D Planner (a graphical simulation tool which allows the user to electronically relate the 3D model to the time dimension in the project schedule), and a VR model for visual planning by simulation of processes respectively. Researchers at Georgia Institute of Technology have developed an Interactive Visualiser allowing the exploration of geometric primitives and operations on a virtual construction site (Ribarsky et al, 1994). Although, this system has great visualisation capabilities, its main weakness is its lack of power of analysis and simulation. It is apparent that the gap between current research and the real construction process is wide.

3. Research Approach

The building block of construction planning methodology is the task. The array of tasks provides the work breakdown structure; the temporal sequencing of tasks is the core of CPA; and the resourcing of tasks provides the input costs of the works. However, what is usually ignored in current methodologies is the fact that task execution occupies space on site, and spaces occupied by one task are often not available either for the execution of other tasks, or the movement of resources between different task execution spaces (for an exception to this see Riley and Sanvido 1995). Our proposition is that the spatial domain is critical to construction projects since one of the main imponderables is the way that task execution block spaces required for the execution of other tasks; at present, the spatial dimension is treated intuitively by experienced planners. We believe that we can move beyond intuition and experience to provide intelligent analysis of the spatial dispersion of construction tasks around the site. New techniques for the analysis of spatial patterns of access have been developed with developed with SERC and EPSRC funding and are now being applied in design decision support. These *space syntax* techniques (Hillier, 1984 & 1996) allow one to represent and quantify the properties of buildings as networks of space open to access. Although these methods were developed and are in use during design for predictive modelling of use and movement patterns in buildings and urban areas, they offer the potential to quantify the degree to which different spaces are critical in the movement network within a construction site as this changes through time. The ability to put numbers to the role played by a space in a whole network will form the basis of the *critical space analysis* (CSA) tool to be developed here.

The aim of this project is to push forward the state of the art in construction project planning by meeting the following objectives:

1) evaluating state of the art in the VR modelling of factory-based processes and identifying the potential for transfer to construction;
2) further developing visualisation tools for critical path analysis;
3) developing tools for *critical space analysis* in construction project planning;
4) producing a visualisation tool which integrates critical path analysis and critical space analysis
5) evaluating the potential for the further development exploitation of the decision support tool.

The Virtual Construction Site system model which will provide the vision for the research is shown in figure 1. The VCS system comprises three elements:

1) the compiling of a project database which integrates relevant geometric, methods, resources and task information;
2) the analysis of time critical and space critical tasks, and the brokering of these two aspects in project planning;
3) the visualisation of the project database through a range of different interconnected graphic windows.

The project database will describe the geometry of both building components and working areas/supports associated with individual tasks. Simple open geometric descriptions (possibly VRML) will be used, but each geometry will also be associated with data on task duration, resources and methods which will encapsulate access requirements for personnel, machinery and materials to that space and restrictions on through movement to other areas of the site during task execution.

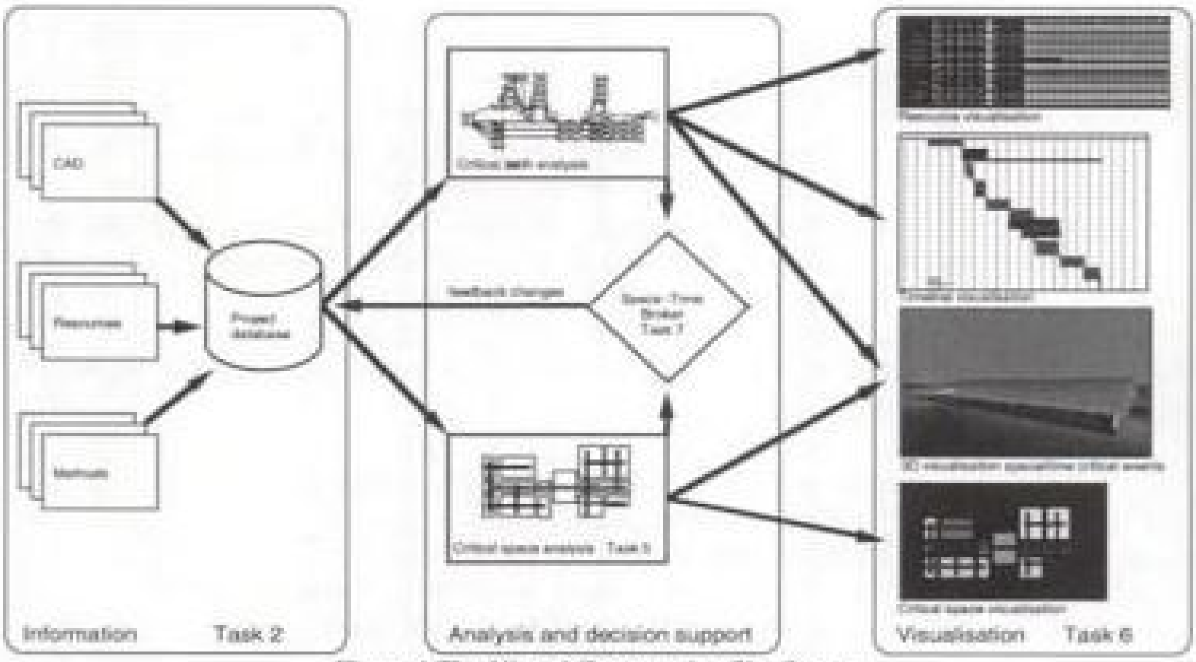

Figure 1 The Virtual Construction Site System

Existing CPA software will be used to analyse the time critical aspects of task schedules, however by linking these to the project database of geometry a simple interactive visualisation of the construction process linked to the Gantt chart will be developed. In itself this is not novel, however by associating geometry describing work areas and access restrictions and making links to CPA, visualisations will be developed that allow one to see the knock on implications of particular tasks on those later in the process. These visualisations will be able to be used strategically to reduce critical bottlenecks and tactically to assist in evaluating the implications of task reassignments following changes to the planned schedule.

The *critical space analysis* tool will add a new kind of functionality to construction planning decision support software. This tool will allow the network of spaces which comprise the construction site and the partially constructed building to be represented and analysed stage by stage through the construction process. Space syntax analysis tools which measure spatial relationships in networks will allow the critical spaces in the network to be pinpointed as that network changes through time and as different tasks restrict through movement. Visualisations will be developed that link CSA and CPA so that both can be tracked interactively through the construction process. We will make use of the fact that the spatial, temporal and resource aspects of the problem will now all be well expressed in the project database and the CSA/CPA analyses to develop the prototype *space-time broker*. This will use multi-criteria optimisation and constraint based techniques to evaluate possible solution strategies for the complex spatial and temporal process of construction planning. A dynamic link to the visualisation tools will ensure that the human and communication aspects of the planning process remain central in the VIRCON system.

4. Development to-date

This section covers the major development to-date for the development of the VRCON. Developments in three major activities are been given in the following sections. These activities are: Productivity analysis case study, Data capture for greating project information database and understanding planning decisions. Progress on technology opportunities and potential is documented in Mahdjoubi et al (2000).

Productivity analysis case study

A pilot case study was performed as part of VIRCON on the School of Health project, Middlesbrough, Teesside. The main objective was to explore the relationships between the spatial configurations of work being carried out on site, and performance and productivity measurements during the project execution. The £6 Million University project was designed by Bond Brian Architects, AMEC as the main contractor and ABB as the Building Services (M&E) contractor. The observation period coincided with the M&E execution stage. The techniques used for performance and productivity analysis was adopted from BRE standard classification[1] by using the application CALIBRE™ (real time performance tool kit). According to the observation programme, 165 observations were completed in 15 days divided into three stages. In stage one observations were made on the ground floor; in stage two, the work being carried out in the first floor was observed; in stage three the second floor was observed.

The performed spatial analysis included movement study of workers (stalking), space conflicts, works clashes between tasks, and provision of work area. Generally the study indicated 30% on average non-productive results (the results might not reflect the overall site productivity as the study was carried out for only 4 weeks).

It was concluded that the non-productive time was a result of inefficient dynamic space planning (space available to perform a task) and It was observed that the long journey distances (due to narrow and restricted accesses to the building), led to lost time on site, and therefore a lack in performance. Although project managers consider workspace in their resources planning, it is identified [Armstrong et al, 1969,] as in the form of offices, accommodation and stage spaces for materials, i.e. a static space. The observation supports the idea that 'space is quiet inflexible so far as movement is concerned,' i.e. the dynamic space [Armstrong et al, 1969].

It was observed that M&E works causes clashes with other construction activities. M&E workers and their activities were major users of space and detailed analysis of the activities and space was imperative.

Data Capture

The objective of this task is to create a project information database, the core of the VRCON prototype development. A number of approaches have adopted in research for the integration of computer applications to facilitate sharing and exchange of data between those applications. These approaches can be grouped under three main headings as follows:

- Software 'Fixing' Approach: This entails linking various software packages through interpreters/translators that transfer information between them. The limitation of this approach is that it prevents the fluent and transparent flow of information between the various software packages. Another disadvantage of the approach is that when additional application software is required, thereby allowing for expandability, will require creation of additional interpreter or translator.

- Blackboard Approach: This approach like the first one uses third party medium for transfer of information between the software packages. Thus allow the fluent and transparent flow of information, but still exhibits the problems related to expandability mentioned above.

- Integrated Databases Approach: The approach provides integration of construction process computer applications through a centralised database. The project information is stored centrally and accessible to all applications. This approach allows information to be controlled and manipulated by the applications themselves without the need for third party medium. This approach is being adopted in this research.

Data Capturing and Re-Structuring

Based on the integrated approach adopted, the data capturing and re-structuring task involved three main activities. These activities are (figure 2 shows the specification of the database system):

1. Data classification and database development:

Identification and classification of building objects: Building elements and components are being identified, classified and structured using standard classification methods (Uniclass and ISO STEP). The main output of this activity is the class diagram. A typical class diagram model is composed of:

- Class objects' name and grouping, attributes and methods (development of Product Breakdown Structure, PBS);
- Inheritance and aggregated relationships between and among the classes and objects.

Database development: This will involve the design, based on the class model above, of database schema and code generation.

UML (Universal Modelling Language) method was adopted for data modelling and database development. The rational behind the selection of this method, compared to other methods such as IDEF1x (IDEntification 1), NIAM, or Express, is based on the comprehensiveness and formalized approach of the method for data modelling and the eventual implementation of the database. UML method is comprehensive in that it contains all the tools needed to structure, and model all information that is transmitted between various disciplines during the design and construction of the building. Another reason for selection of this method is the ease of use and understanding of the method by the researcher. UML is also language independent that the database can be implemented in any computer languages. Popkin's 'System Architect 2001' is being used as a tool for implementing UML.

The following sections introduce the linkage of CAD and CPM (critical Path Method) with the proposed database.

2. CAD data linking to the database:

The aim of this activity is to investigate how CAD data can be linked (or connect) with the database. With this in mind, the objectives of the this are;

- focus on optimising external database connectivity facilities within the CAD system, and
- Take advantage of the customisation capability of the system.

3. Linkage to CPM software

This aim is to link project management software (Critical Path Method using Work Breakdown Structure, WBS) with the central database. This includes mapping the

MSProject data base onto the central database. In this method, activities, resources, and cost will be integrated with the database. The ultimate objective is the dynamic integration of WBS and PBS.

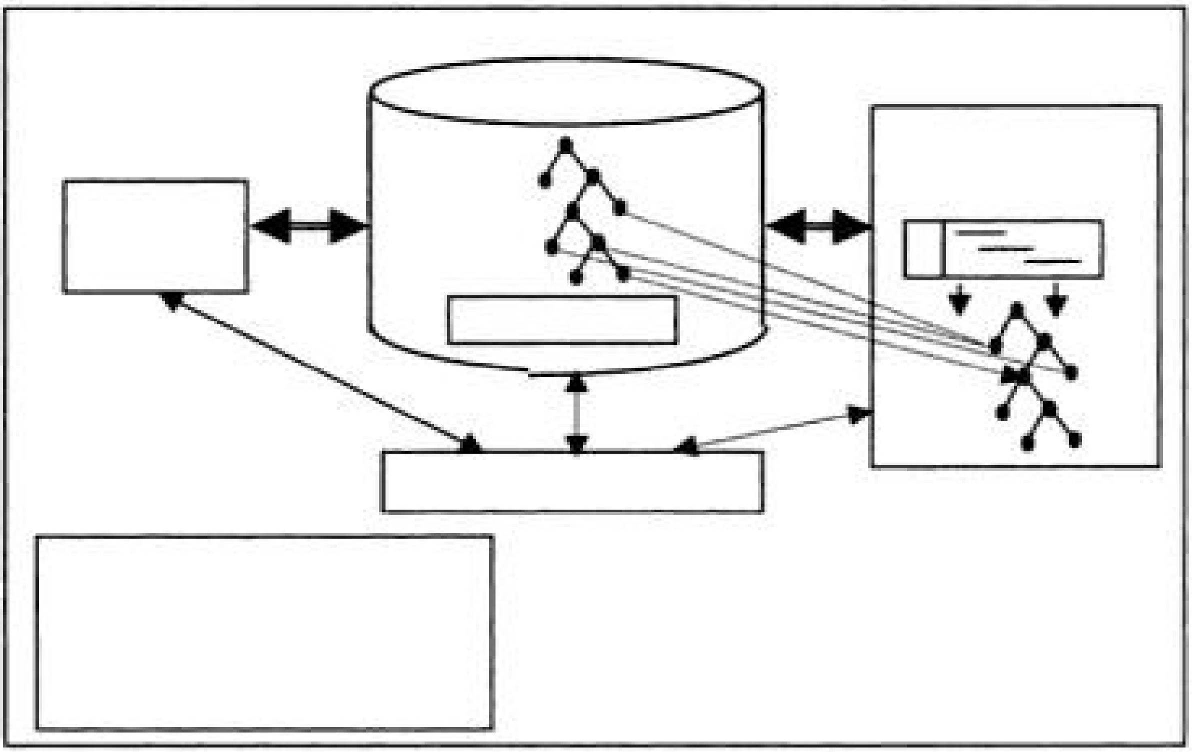

Figure 2: System Architecture of the database

Understanding Planning Decisions

This is the requirements capture stage of the VIRCON project. We need to know how construction planners actually take decisions regarding the project. Remarkably, there is little empirical work on this topic, despite considerable theoretical work about what planners ought to do. We need to know more about :

- The context of construction project planning – project and firm
- Sources of information
- The flow of information
- Software tools currently in use
- Decision-making criteria
- What their "wish-list" for a space-time broker might be

The principal method deployed will be process-mapping using Visio Technical, supported by interview data. (The interviews will concentrate on the long-term pre-construction planning process.) We intend to work with some 20 planners from all the VIRCON collaborating companies to establish the requirements for the space-time broker.

The investigation will look at three interrelated aspects of construction planning:

- Temporal dynamics (e.g. critical path method)

- Spatial Statics (e.g. site layout)
- Spatial Dynamics (i.e. how operatives/materials/plant move around site)

The proposed critical space analysis is intended to add value particularly in the problem of understanding Spatial Dynamics, and this is where our investigations will be focused.

4. Conclusions

The main objective of this paper was to introduce and discuss the development of the VIRCON. Previous literature and industrial case studies have identified the need for a strategic planning system that can aid construction managers in the evaluating, visualising and optimising construction schedules. In this context, the ultimate aim of the VIRCON is to provide a desktop strategic decision support tool which will allow planners to trade off the temporal sequencing of task with their spatial distribution within a virtual reality environment. The result would be a more robust and rehearsed project schedule.

Acknowledgement
The research team would like to acknowledge the financial support of EPSRC for this project.
The research team would also like to acknowledge the contribution of the industrial partners. These are: Carillion (Dr G. Lucken, Research Project Manager), WS Atkins (B. Short), Stent Foundation (J Findlay), Kvaerner Construction (S. Hulme), Bond Brian Partnership (J. Bryan), AMEC (A. Neale), Service Design Assocaite (P. Hoyes), Turner and Townsend (S. Armitt).

References

1. Armstrong-Wright, A. T. [1969] '*Critical Path Method: Introduction and Practice*', Longmans
2. Boyd L., (1998), Digital Factories *Computer Graphics World*, May 1998, pp. 45-52.
3. Brigewater, C. et al. (1993), Application of virtual reality to Computer-Aided Building Design. In *Visualisation and Intelligent Design in Engineering and Architecture* Computational Mechanics Publications, London:213-217.
4. Carr, B. and Winch, G. M. (1998) *Construction Benchmarking : an International Perspective* Bartlett Research Paper No. 3.
5. CALIBRE™ 2000, Building Research Establishment (BRE), Publication of Centre for Performance Improvement in Construction (CPIC), UK
6. Construction Task Force (1998) *Rethinking Construction* London, HMSO.
7. Hendrickson, C., Zozaya-Gorostiza, C., Rehak, D., Baracco-Miller, E. and Lim, P. (1987) Expert System for Construction Planning, *Journal of Computing in Civil Engineering* 1 4, 253-269.
8. Hillier, B. (1984) *The Social Logic of Space* Cambridge, Cambridge University Press.
9. Hillier, B. (1996) *Space is the Machine Cambridge* Cambridge University Press.
10. Hillier B., & Penn A. (1993) Virtuous Circles, Building Sciences and the Science of Buildings: using computers to integrate product and process in the built environment, in *Informing Technologies for Construction, Civil Engineering and Transport*, in Eds., Powell J. A., & Day, R., Brunel University with SERC, London, pp. 283-300.
11. McKinney, K., and Fischer, M. (1997) 4D Analysis of Temporary Support, *Computing in Civil Engineering, Proc. of 4th Congress*, June 16-18,.
12. Mahdjoubi, L & Lockley S., (1996) *AutoCAD. A progressive course* DP Publications: London.
13. Mahdjoubi, L. & Wiltshire, J. (1996) Computer mediated architect-client design collaboration. *INCIT 96 Proceedings. International construction information technology conference*. The Institution of Engineers: Sydney, Australia. pp. 13-18.
14. Mahdjoubi L, Heesom, D., Winch, G., Penn, A., Kelsey, J., Edkins, A., North, S., Dawood, N., Hobbs, B., Akinsola, A, Mallasi, Z., (2000), A *Critical Review of Decision Support Systems for Construction Project Planning*, CONVR 2000 conference, Middlesbrought, Sept, 2000.

15. Morad, A.A., and Beliveau, Y.J. (1991), Knowledge-Based Planning System, *Journal of Construction Engineering and* Management 117 1, 1-12.
16. Nutt, B, McLennan, P. and Walters, R (1998) *Refurbishing occupied buildings: management of risk under the CDM Regulations*. Thomas Telford: London
17. Penn, A., Conroy, R., Dalton, N., Dekker, L., Mottram, C., Turner , A., (1995) Intelligent Architecture: User interface design to elicit knowledge models, in Macintosh, A. & Cooper, C. (eds) *Applications and Innovations in Expert Systems III* SGES Pubication, Oxford, 335-348.
18. Penn, A., Dalton, N., Dekker, L., Mottram, C. & Nigri, M., (1997) Intelligent Architecture: Desktop VR for Complex Strategic Design in Architecture and Planning, in Seidel R.J. & Chatelier, P.R. (eds) *Virtual Reality, Training's Future?, Perspectives on Virtual Reality and Related Emerging Technologies*, Defense Research Series, Vol 6, Plenum Press, New York, 1997.
19. Retik, A. (1996), Construction Project Planning: A Virtual Reality Approach, *IPMA 96, World Congress on Project Management* Paris.
20. Ribarsky, W et al., (1994), Visualisation and analysis using virtual reality. *IEEE Computer Graphics and Applications*, January: 10-12.
21. Riley, R and Sanvido, V (1995) Patterns of construction-space use in multi-story buildings *Journal of Construction Engineering and Management*, December, pp 464-473.
22. Soh, C., Phang, K. and Wong, W. (1993), An Integrated Intelligent System for Scheduling Construction Projects, *Proceedings of Institution of Civil Engineers* Nov, 156-162.
23. Tommelein, I, Levitt, R and Hayes-Roth, B (1992) Site Layout Modelling : How can Artificial Intelligence Help? *Journal of Construction Engineering and Management* 118, 3, pp 749-766.
24. Tommelein, I, Levitt, R and Hayes-Roth, B (1992) SightPlan model for site layout. *Journal of Construction Engineering and Management*, 118, 4, pp 749-766.
25. Williams, M. (1996), Graphical Simulation for Project Planning: 4D-Planner, Computing in Civil Engineering *Proc. of 3rd Congress*, June 17-19 404-409.
26. Wilson et al., (1996) *Virtual reality for industrial applications: Opportunities and limitations*. Nottingham, Nottingham University Press.
27. Wijensundera, D.A. Olomolaiye, P.O. & Harris, F.C. (1991) Dynamic simulation applied to materials handling in high-rise construction. *Computers & Structures* 41(6), pp.1133-1139
28. Winch, G. M. (1994) *Managing Production; Engineering Change and Stability* Oxford, Oxford University Press.
29. Zhang, P. et al. (*forthcoming*) Location optimisation for a group of tower cranes *Journal of Construction Engineering and Management*.
30. Zouein, P.P. (1995), *MoveSchedule: A Planning Tool for Scheduling Space Use on Construction Sites*, PhD Dissertation Abstract, The University of Michigan.