Technology Opportunities and Potential for The Virtual Construction Site

Emerging Research Initiatives

David Heesom and Lamine Mahdjoubi

This research is funded by the Engineering and Physical Sciences Research Council's research programme award no GR/N00876 as part of the Innovative Manufacturing Initiative
Technology Opportunities and Potential for The Virtual Construction Site

Emerging Research Initiatives

David Heesom and Lamine Mahdjoubi
Executive summary

This document presents Volume 1 of the Technology Opportunities and Potential for the Virtual construction Site (VIRCON) project. The report reviews a significant body of research both in the United Kingdom and Overseas that has been, or is currently being investigated in the area of construction project planning. The aim is to identify gaps in these research areas, and present an outlook for potential developments of the VIRCON project. The following presents a brief summary of the main findings:

1. Work in the field of construction planning is divided into 3 main sections. The first section involves the simulation of the construction processes to assist the planning stage. Research in this area varies from modelling the activities using mathematical algorithms to actual visual simulation of activities on the construction site to identify incorrect schedule logic.

One of the main research areas at present is 4D CAD. This process links 3 dimensional CAD components of a design, to the temporal aspect of activities required for component construction, as depicted on the schedule. On the basis of these fundamental developments, various research efforts have been undertaken, which led to the emergence of several trends.

Some studies focus on the user of the 4D tool to analyse the logic of the construction schedule prepared by the planner. Others attempt to assist the planner during the planning stage by utilising intelligent CAD objects to generate the construction schedule. In addition, research efforts have been devoted to the development of a central product model from which all information is retrieved to generate 4D CAD simulations.

However, existing 4D systems are mainly focused on the integration of 3D building components with schedule information. In order for the next generation of 4D CAD to have a significant impact on the construction planning phase and aid planners in their decision making process, it is critical that it considers the spatial implications of construction activities.

2. The second section of this report deals with the scheduling of space usage on the construction site. Work in this field is divided into 2 sections, investigating material space usage and the spatial requirements of activity execution. Work undertaken in the area of material space usage recognises that the dynamic location of materials on the construction site has implications on space usage and hence the program of works. Progress on research aimed at developing space ‘templates’ was reviewed. These templates depict the spatial requirements of materials throughout the duration of the construction project and are used by planners to create site layouts at various time intervals. A similar field of work has developed prototypes that use expert systems and knowledge based systems to provide layouts of material on site, during various stages of construction.
These research efforts highlight the dynamic nature of materials location and movement on site with emphasis on its spatial requirements. Some of the systems developed only embody knowledge specifically for certain construction projects. In addition, they only considered the initial layout of the site prior to work commencing and space being utilised by constructed components.

Generating site layouts using templates added some dynamic capabilities to the layout conundrum. This method allowed the planner to develop site layout plans for various time frames within the construction process, relating to activities occurring during the time frame. Although contributing some dynamic ability, the templates did not take into account diminishing materials and area variation. The concept of templates to depict construction resources could be a potential benefit to VIRCON. These templates could be used to represent certain generic items with spatial attributes that could be varied by the planner.

More recently, some effort has been directed towards the simulation of materials movement on complex construction sites. This work is directed at developing a decision-support system to determine the optimum route for the movements of materials around the site based on spatial constraints. Allowing simulation and rehearsal of possible scenarios, the system facilitates planning to select the best available route of material movement due to unforeseen circumstances. This system could be employed as a support tool for construction space planning, to provide a more comprehensive project plan. The routing of materials is subsequent to hard constraints and these constraints could be in the space consumed by materials or activity execution.

Work has also been carried out to investigate the use of space during activity execution. This has identified that in order for an activity to be executed, four types of space are required: Execution space, Storage area, Route paths and Access points. This work also introduces the potential of workspaces to be shared, and the effect of space sharing on the task duration. Space density is a numerical value between 0.1 and 1.0 highlighting the ability of a space occupied by an activity to be shared by another activity space. The Space Capacity Factor (SCF) represents the relationship between the space available for activity execution and the space required. Using the SCF the productivity can be determined in order to review task duration.

3. The final section of work reviews progress in the identification of time-space conflicts during construction planning. In addition to material space conflicts, this field of work stresses that activity execution occupies space, and spaces occupied by one task are often not available for the execution of other tasks, or the movement of resources.

In the material layout domain, work has been carried out to identify important time frames relating to the construction schedule. Within these time frames, site layout plans resulting from occurring activities are developed. Conflicts between material positions can be detected, and these can be solved by amendments being made to the schedule. Although providing solutions to the layout conflicts, this system has the same inherent disadvantages as those described above.
Although dynamic properties are applied to create site layouts in different time frames, no account is made for decreasing material space during the time period.

The activity execution space field has also produced conflict analysing systems. The most recent of these applies the 4D CAD principle to detect time-space conflicts. This work describes space as an object, in much the same way as a building component is described, and uses this space object in a 4D simulation. Any conflict between these spaces can be detected and categorised regarding to their severity. This addition of space requirements to 4D simulations allows for a more robust rehearsal of the project sequence, however the space is modelled as a static object. In the simulation, it is always assumed that the space requirements for the activity remains constant throughout the duration of the task, although it is widely accepted that this is not the case. During the undertaking of an activity, operational processes can envelop various spaces at different stages.

In summary, from the reviewed work, it emerged that 4D work has failed to consider the spatial requirements of activities and their dynamic nature. Although recent developments looking into material space scheduling have taken into account the spatial dynamics, their applications in space planning have been limited. To fully represent a space loaded construction schedule, consideration must be given to the dynamic properties of activities. This is an area to be fully considered by VIRCON system. This study also revealed the limitations of efforts directed at developing expert systems, as these only provide solutions for certain scenarios. VIRCON should be designed to be a strategic planning tool to allow the rehearsal, through simulation, of on-site processes. This will allow better strategic planning, and also allow scenario planning in order to enable faster and more appropriate responses to the unexpected on site.

In addition, this review has highlighted the potential opportunities to be incorporated into the VIRCON development. The concept of templates to represent generic construction facilities could potentially benefit the system development. These could be used to represent not only materials, but also other space-related objects such as plant and temporary works. Another area for potential inclusion in the VIRCN system is the principle of space sharing. At present, the concepts reviewed in this report, such as space density and the Space Capacity Factor could provide benefits to VIRCON by allowing a more realistic modelling of activity space.
TABLE OF CONTENTS

1.0 General Introduction for technology opportunity and potential .................................................1
  1.1 Identification of Research problem ...............................................................................................1

2.0 Introduction to volume 1 ..................................................................................................................2
  2.1 Structure of report..........................................................................................................................2

3.0 Simulation of the construction process ..........................................................................................3
  3.1 Four Dimensional Computer Aided Design ..................................................................................3
    3.1.1 Background.............................................................................................................................3
    3.1.2 4D annotations .........................................................................................................................5
    3.1.3 Design Cost Schedule Integration.............................................................................................5
    3.1.4 Construction Method Models ...................................................................................................6
    3.1.5 Using 4D CAD to Evaluate the Executability of a Construction Schedule .......................6
    3.1.6 Walt Disney - Imagineering .....................................................................................................7
  3.2 Using 3D animation to optimise operational level planning in the design and
  construction of complex construction projects .................................................................................7
    3.2.1 Background.............................................................................................................................7
    3.2.2 Objectives ...............................................................................................................................7
    3.2.3 Methodology ............................................................................................................................7
    3.2.4 Results .....................................................................................................................................8
  3.3 Intelligent system for visual simulation of construction projects .................................................9
    3.3.1 Background.............................................................................................................................9
    3.3.2 Objectives ...............................................................................................................................9
    3.3.3 Methodology ............................................................................................................................10
    3.3.4 Results ....................................................................................................................................13
  3.4 Virtual Construction Environment for Project Planning ...............................................................13
    3.4.1 Background.............................................................................................................................13
    3.4.2 Objectives ...............................................................................................................................13
    3.4.3 Methodology ............................................................................................................................14
    3.4.4 Results ....................................................................................................................................15
  3.5 A Virtual Environment for modular building construction .........................................................15
    3.5.1 Background.............................................................................................................................15
    3.5.2 Project aims ............................................................................................................................16
    3.5.3 Methodology ............................................................................................................................16
    3.5.4 Results ....................................................................................................................................17
  3.6 Simulation in Construction .............................................................................................................17
    3.6.1 Background.............................................................................................................................17
    3.6.2 Objectives ...............................................................................................................................18
    3.6.3 Methodology ............................................................................................................................18
    3.6.4 Results ....................................................................................................................................19
  3.7 Open Systems for Construction ....................................................................................................19
    3.7.1 Background.............................................................................................................................19
    3.7.2 Project Aims and objectives ......................................................................................................19
    3.7.3 Methodology ............................................................................................................................19
    3.7.4 Results ....................................................................................................................................20
  3.8 CONPLAN: construction planning and buildability evaluation in an integrated and
  intelligent construction environment .................................................................................................21
    3.8.1 Background.............................................................................................................................21
3.8.2 Objectives

3.8.3 Methodology

3.8.4 Results

3.9 VTT Finland, Construction IT Research projects

3.9.1 Background

3.9.2 Objectives

3.9.3 Methodology

3.9.4 ProMoTe

3.10 Design Build Knowledge Information Slider System (DBKISS)

3.10.1 Background

3.10.2 Methodology

3.11 Virtual Construction (VIRCON) – Australia

3.11.1 Background

3.11.2 Objectives

3.11.3 Methodology

3.12 A Virtual Reality System for Site Layout Planning

3.12.1 Background

3.12.2 Objectives

3.12.3 Methodology

3.12.4 Results

3.13 Discussions and Summary

4.0 Space Requirements for Construction

4.1 SightPlan

4.1.1 Background

4.1.2 Objectives

4.1.3 Methodology

4.1.4 Results

4.2 MoveCapPlan

4.2.1 Background

4.2.2 Objectives

4.2.3 Methodology

4.2.4 Results

4.3 Virtual Construction Materials Router

4.3.1 Background

4.3.2 Objectives

4.3.3 Methodology

4.3.4 Results

4.4 4D space planning for Construction Work Spaces

4.4.1 Background

4.4.2 Objectives

4.4.3 Methodology

4.4.4 Results

4.5 Space Constrained and Resource Constrained Scheduling System (SCaRC)

4.5.1 Background

4.5.2 Objectives

4.5.3 Methodology

4.5.4 Results

4.6 Discussions and Summary

5.0 space time conflicts on construction sites

5.1 Modelling the Space Behaviour of Construction Activities
5.1.1 Background..............................................................................................................41
5.1.2 Objectives ................................................................................................................41
5.1.3 Methodology ............................................................................................................42
5.1.4 Construction Space Planning Model .................................................................43
5.1.5 Results .....................................................................................................................47
5.2 MoveSchedule .............................................................................................................48
5.2.1 Background ..............................................................................................................48
5.2.2 Objectives ................................................................................................................48
5.2.3 Methodology ............................................................................................................48
5.2.4 Results .....................................................................................................................51
5.3 Formalisation of time-space conflict analysis .........................................................52
5.3.1 Background ..............................................................................................................52
5.3.2 Objectives ................................................................................................................52
5.3.3 Methodology ............................................................................................................52
5.3.4 Results .....................................................................................................................55
5.4 Discussions and Summary .........................................................................................56
6.0 Industrial research ....................................................................................................58
6.1 Overview ......................................................................................................................58
6.2 WS Atkins Consultants ..............................................................................................58
6.2.1 Background ..............................................................................................................58
6.2.2 Examples ..................................................................................................................58
6.3 Stent Foundations ......................................................................................................59
6.3.1 Background ..............................................................................................................59
6.3.2 Examples ..................................................................................................................59
6.4 Discussions and Summary .........................................................................................60
7.0 Overall Conclusions .................................................................................................61
8.0 References ..................................................................................................................63
Table of Figures

Figure 1: Breakdown of Technology Opportunities and Potential ........................................ 1
Figure 2: Comparison of basic 4D model and 4D model with annotations ........................... 5
Figure 3: The functional architecture of VR Planner .......................................................... 11
Figure 4: Main components of the VR Planner Prototype .................................................. 12
Figure 5: Overview of Virtual Construction Environment ................................................ 15
Figure 6: Software architecture ........................................................................................ 17
Figure 7: The overall OSCON architecture ........................................................................ 20
Figure 8: CONPLAN system architecture ........................................................................ 22
Figure 9: MoveCapPlan Layout Planning and Control System ............................................ 32
Figure 10: Data Flow in the VCMR .................................................................................. 33
Figure 11: Productivity - SCF Relationship ........................................................................ 37
Figure 12: Types of Space in the Construction Space Model .............................................. 44
Figure 13: Planning Process Model ...................................................................................... 46
Figure 14: Flow Chart of Space Scheduling Algorithm ....................................................... 51
Figure 15: Time-Space Conflict Taxonomy ........................................................................ 54
Figure 16: Outline of 4D Workplanner Time Space Conflict analyser ............................... 55
1.0 GENERAL INTRODUCTION FOR TECHNOLOGY OPPORTUNITY AND POTENTIAL

The purpose of this report is to provide a background to the research being undertaken as part of the Virtual Construction Site project. The report is divided into 3 volumes. Volume 1 focuses on current and emerging areas of work carried out in construction project planning. Volume 2 provides a comprehensive review of CPA software. The report provides a technical audit of available CPA software along with proposed future developments of the software and implications on the VIRCON project. Volume 3 assesses emerging technologies that can aid in the development of the VIRCON system. This report provides a review of interoperability issues, virtual manufacturing processes and a review of e-commerce developments. Figure 1 shows the components of the technology opportunities and potential report.

1.1 Identification of Research problem

It has been reported that there is a looming skills gap in the construction industry amongst those with the expertise to plan major construction projects (Dawood et al, 2000). There are now 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.

The basic component of a construction schedule is the task or activity. The array of tasks provides the work breakdown structure, the temporal sequencing of tasks is the core of Critical Path Analysis (CPA) and the allocation of resources to tasks provides the cost of the works. What is usually ignored in current methodologies however is the fact that the execution of the task occupies space, and spaces occupied by one task are often not available either for the execution of other tasks, or the movement of resources. The principle motivation behind the Virtual Construction Site is that the spatial domain is critical to construction projects since one of the main imponderables is the way that task execution spaces are required for the execution of other tasks. At present, experienced planners treat the spatial dimension intuitively. The project proposes that project planning can move beyond intuition and experience to provide intelligent analysis of the spatial dispersion of construction tasks around the site.

![Figure 1: Breakdown of Technology Opportunities and Potential](image-url)
2.0 INTRODUCTION TO VOLUME 1
This report reviews current and emerging developments in the construction planning process in order to highlight its potential advantages and limitations, including its implications on VIRCON. As a result, a review was carried out of progress involving both academic and industrial research.

2.1 Structure of report
The following report is structured into four sections reviewing various research efforts in the UK and elsewhere relating to construction planning and visualisation.

The first section examines ongoing work relating to the visualisation of construction tasks on the schedule and how this is utilised. The second section reviews work relating to the space requirements and modelling of construction activities to assist in the planning scenario. The third section provides a review of work that has progressed these two concepts further to identify space-time conflicts that occur on construction sites. The final section of the report provides an insight of some of the work currently being carried out by the industrial sector within the UK. This includes a review of work being undertaken by the project collaborators and elsewhere.
3.0 SIMULATION OF THE CONSTRUCTION PROCESS

“Clearly . . . any real body must have extension in four directions: it must have Length, Breadth, Thickness, and Duration.”
H.G. Wells, The Time Machine (1895)

In order to generate a robust construction schedule, a rehearsal of the schedule in a virtual domain can be undertaken. In some cases this rehearsal presents graphical objects to represent the building components whilst others display the processes as models representing the various activities. Each of these techniques presents the capability to somehow visualise and analyse derived construction schedule to highlight potential errors in the program logic. This section reviews work undertaken to simulate the construction process to highlight such errors.

3.1 Four Dimensional Computer Aided Design

3.1.1 Background

The underlying principles of 4D CAD have been used since 1987 (Fischer and Kam, 2001). The term 4D CAD is defined as providing the ability to represent the construction plan graphically (Williams, 1996), producing a 4D simulation involves linking a 3D graphic model to a construction schedule through a third party application (Collier and Fischer, 1996; McKinney et al 1996). For example, the construct wall task shown on the project schedule is linked to the 3D CAD object representing the wall. The 3 dimensions of the model (i.e. x, y, z) are linked to the temporal dimension on the project plan, hence 4 dimensional modelling (Knutsson, 2000; Phair, 2000; Goldstein, 2001a).

4D planning presents a new method to undertake construction scheduling and advances the principles of planning past the Gantt chart (Richmoller et al,. 2001; Winch et al. 2000). Cherneff (1991) discussed the principle of integrating Computer Aided Design (CAD) data with a construction schedule. Using the developed ‘Builder’ system, a knowledge base extracted geometric product information from a CAD drawing and generated activities for each product. The utilisation of 4D visualisation allows a more intuitive comprehension of the construction process that is easier understood than traditional 2D drawings and schedule information (Bergsten, 2001).

Some early work in the area of 4D CAD simulations was undertaken by Coles and Reinschmidt (1994) who demonstrated that creating a 3D model over time assisted in the planning process. It can be seen that 4D CAD is a natural progression to 3D CAD models as it adds a further dimension (Phair, 2000) however, the use of these 4D simulations fluctuates, and various parties view 4D CAD as being an appropriate tool to assist in assessing different areas of the overall construction process. The collaboration between clients and designer is an area that has been identified as problematic. Rad and Khosrowshahi (1997) highlight that although 3D visualisations have gone some way to closing the communication gap between clients and designers 4D CAD is allowing this gap to narrow even further.

4D CAD was described by Barrett (2000) as having the potential to provide an improved relationship between construction designers and constructors. 4D CAD is currently extensively used as an explanatory and descriptive tool. Work undertaken by McKinney et al. (2001) demonstrates that at present 4D CAD is used extensively during meetings to explain designs and describe work packages. Another prominent
use of 4D visualisations has thus far been in the marketing and pre-construction phases of a project. Webb (2000) highlights an example of 4D CAD utilised as a presentation tool by Bovis, USA. During the construction of the Lynchburg General Hospital, Virginia, 4D simulations were used to demonstrate construction work sequencing. 4D CAD was utilised during the construction phase of the San Mateo County Health Centre, USA, to assist the contractor during site operations (Collier and Fischer 1996). The trial implementation of 4D modelling on various construction projects has demonstrated significant benefits to activity sequencing and production planning (Riley, 2000). A further example of using 4D principles to view the processes of construction is presented in the Gallicon project (Sun et al., 2000) and 4D modelling has also been used extensively for the simulation of the Logan International airport modernisation project. During this project, 4D simulations provided crucial information to airport planning bodies as it enabled the state of the airport to be visualised at a discrete point in a way that a 3D model of the final project could not (Edwards and Zeng, 1997).

Presently, the most productive use of 4D simulations would be on large, complex projects where the investment required to develop the simulation would be justified. Once developed the simulations could be utilised to identify and develop alternatives when disruption to the original plan occurred. It is envisaged that the use of 4D simulations could assist in the halving of the waste costs associated with construction projects (Webb, 2000).

Zhang et al. (2000) identify that although 4D CAD is mainly used for the simulation of the component level of the construction process, the technology lends itself to assisting in the site layout paradigm (discussed further in Section 4.0). Work undertaken by Zhang et al. (2000) presents a 4D site management tool ‘4D Graphics for Construction Planning and Site Utilisation’ or 4D-GCPSU. This system presents the planner with a 4D representation of the constructed product whilst allowing materials to be included into the simulation model providing a more robust site layout plan. The zone used during the construction phase is also an area of application for 4D CAD. Akbas et al. (2001) discuss the use of 4D CAD to analyse the ‘zones’ or areas used by construction operations during various stages of the construction sequence. This information can then be utilised to plan activities that will take place in various locations on the site.

Further work is being undertaken to exploit real time technologies by Kähkönen and Leinonen, (2001a). Software has been developed that allows the viewing of construction progress using a Virtual Reality Modelling Language (VRML) interface. This 4D browser links Industry Foundation Class (IFC) based 3D product model data to schedule data. The resulting 4D model can then be viewed through a web interface (Kähkönen and Leinonen, 2001b).

The application of 4D CAD principles to the construction industry is the basis of much research currently being carried out at various academic institutions and forms the basis of various research projects. One of the most established institutions is the Centre for Integrated Facility for Engineering (CIFE) at Stanford University, USA. Since the initial project in 1994 the 4D research group has undertaken and is still actively undertaking various work involving 4D CAD, under the direction of Martin Fischer.
3.1.2 4D annotations
McKinney and Fischer (1998) describe the current process of project planning as utilising a ‘mental 4D model’.

4D annotations were an area of research at CIFE aimed at making 4D models ‘explanative and predictive’. The basis of the work was to add annotations to a 4D model 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, for example cost.

This work reported that current 4D systems lack the functionality to visually communicate non-descriptive information (for example why activities are scheduled in a certain way). The research investigated the type of annotations necessary by compiling questions asked by planners. As a result, a mechanism was developed to associate the content of the annotation with the 3D component of the building.

The proposed annotator system comprised two modules. The feature assigner allows planning features such as the requirement of the component to be supported by another component. The output of the feature assigner is a 4D model with planning features. This can be used as input into a planning system that requires knowledge of component relationships. The second module is the annotator environment. This provides a graphic environment for the user to view various types of planning information (McKinney and Fischer, 1998).

Figure 2: Comparison of basic 4D model and 4D model with annotations
(Source: McKinney-Liston et al. 1998)

3.1.3 Design Cost Schedule Integration
Another project being carried out at CIFE, used a 4D model of a construction facility to assist with the day-to-day planning of construction work. The 3D model used was also shared between the whole project team throughout the entire design. This was
linked to a cost-estimating program for automated quantity takeoff. The goal of the project was to explore 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. The integrated design, cost, and schedule model records and communicates the status of the construction process (Staub, 1999).

3.1.4 Construction Method Models
This project, also undertaken at CIFE, developed customisable construction method model templates (CMMT). These templates generalised activity generation and sequencing knowledge. This information is then captured in user-selected construction method models.

Construction Method Models build on the principles of CARS (Construction Actions Resource Sequencing constraints) by allowing the construction planner to model activities required for a particular method. Planners can use these method templates to define and store general construction method knowledge and this is then applied to the product model to generate activities with explicit CARS entities (Fischer et al., 1999). The CMMT have been implemented in the Construction Method Modeller (CMM) planning system using Intellicorp's PowerModel object environment. Jacobus Technology's Schedule Simulator software, VRML, and Java3D are used to visualise and manipulate the resulting 4D models. CMM has been used to model approximately 50 construction methods for reinforced concrete building and process plant construction. The construction methods modelled have between one and eleven constituting activities.

3.1.5 Using 4D CAD to Evaluate the Executability of a Construction Schedule
This research was undertaken by Koo and Fischer (2000), at CIFE, Stanford University. The aim is to determine whether a 4D CAD model can assist in the identification of scheduling problems that were overlooked in when using traditional scheduling techniques.

During the course of this research 2D drawings and a CPM schedule of activities were presented to students for a project that had recently been completed. During the project several conflict problems arose due to incorrect schedule logic and the students were asked to identify these retrospectively. Using the 2D drawings and the schedule, the students were unable to detect any of the conflicts that had occurred on the site however; once a 3D and 4D model of the construction phase had been constructed they correctly identified several of the constructability problems (Koo and Fischer, 2000).

This work concluded that a 4D model provides the ability to communicate a schedule more clearly than traditional techniques. Using 4D technologies allowed relatively inexperienced construction professionals to identify problems that can be overlooked by experienced personnel in the traditional schedule formats.
3.1.6 Walt Disney - Imagineering
An application of the 4D concepts has been carried out as a collaborative effort between CIFE and Walt Disney Imagineering (WDI) (Goldstein, 2001b). Using a 4D prototype tool the construction of the Paradise Pier portion of Disney's California Adventure was planned. The research group is also using the 4D tool on the Frank Gehry designed Disney Concert Hall in Los Angeles to help coordinate subcontractors, study the constructability of the design, and verify the executability of the construction schedule.

In addition, the research group in collaboration with WDI is investigating the functionality needed for a 4D environment to serve the needs of the Paperless Design Project. This research is looking at how engineers and project managers can utilise 3D and 4D CAD to manage and minimise risk throughout all stages of a construction project, effectively communicate the design, and rapidly explore design and construction alternatives (Fischer, 2001).

3.2 Using 3D animation to optimise operational level planning in the design and construction of complex construction projects

3.2.1 Background
Dr. Anthony Songer at the University of Colorado in collaboration with Flatiron Structures Company investigated this area of work. The findings of the report are documented in a technical report to the Colorado Advanced Software Institute (CASI) entitled ‘Emerging Technologies in Construction: Integrated Information Processes for the 21st Century’.

3.2.2 Objectives
The overall aim of this research was to demonstrate that the use of 3D visualisation during the planning and scheduling phase of a construction project could substantially improve the quality of the project schedule. In achieving this aim the project had several further objectives. The work aimed to establish whether 3D technology had benefits over traditional 2D paper designs when creating and reviewing construction schedules and subsequently whether this technology was more effective for planning specific construction processes. The project aimed to determine whether the 3D animation of construction sequences facilitated a clear evaluation of construction schedules and finally to identify the primary considerations for integrating this technology into an existing project management program.

3.2.3 Methodology
The methodology of this work was split into five phases: establishing ‘qualitative’ and ‘quantitative’ measures; developing a testing model; testing and data collection; data processing; and data analysis.

The first phase determined the criteria that would characterise improved scheduling performance. The schedules were characterised into two types, ‘correct’ and ‘good’ schedules. Correct schedules had a number of missing activities, a number of missing relationships and a number of invalid relationships whereas a good schedule had project end dates, showed a number of critical activities and presented total float values.
The second phase involved the creation of construction data for a power plant pipe rack. This project was chosen as it incorporated varying levels of construction complexity i.e. concrete, steel and pipe works. The data was generated in 3 differing formats, 2D drawings, 3D drawings and a walk through visualisation that allowed the planner to move through and rotate the model into any perspective. Fifty planners of varying experience were provided with these forms of visualisation.

The third phase of the research involved asking the planners to utilise the information provided to them regarding the pipe rack and extract construction activities for the physical elements of the facility. They were then required to develop an activity sequence using a given list of construction activities. Once these had been provided the next phase transferred each participants schedule into Primavera Project Planner (P3). This allowed the specific information on each schedules critical activities, total float values, resource usage rates, start / finish dates and loop errors to be determined.

Finally, the results obtained from the participants were analysed. The characteristics of the schedules were measured against those set out in the first phase allowing the quality of the participants schedule to be determined. For each of the 'good' schedules the duration, the critical path, the float and the resource fluctuation was analysed and compared.

3.2.4 Results
The results were analysed firstly in terms of the quality of the schedules, which were produced i.e. the correct schedules and the good schedules, as previously defined.

The results first concentrated on the ‘correct’ schedules. It was analysed from these that the schedules developed based on 2D hard copies had more missing activities than the schedules developed from 3D hard copy or the walk through environment. However the results showed little difference in the number of missing activities between 3D drawings and 3D CAD walk through representation, demonstrating that for basic scheduling there is little advantage in the multi-dimensional capabilities of a walk through. In addition, the findings showed that schedulers using the 3D walkthrough model did a flawless job of delineating all the necessary relationships between the schedule activities. The inability to fully comprehend the pipe work required from the 2D drawings caused many errors in the schedule logic, however the walkthrough schedule showed an advantage over the 3D drawings. When analysed the schedules produced using the walkthrough also showed no logic errors i.e. errors that constituted physical impossibilities, whilst the schedules produced using the 2D drawings had a much higher rate.

The next analysis considered the schedules classified as ‘good’. From the results, it was shown that by using the 3D drawings in comparison to 2D drawings, the end date of the schedule was reduced by approximately 7 days whilst the schedules produced with the aid of the walkthrough were even shorter (approximately 10 days). The schedules using the hard copy drawings also produced more critical activities than those produced with the walk through. One interpretation of this is that schedulers were more confident in overlapping activities when using the walk through. Analysis of the results showed that the pipe work flowed more smoothly in the walk through based schedules than the other work types (i.e. concrete and steel),
demonstrating that the complexity of the project is a significant issue when using 3D visualisations during planning. This is a critical factor when integrating this technology into an existing planning system. The time and effort required to produce a 3D model may be considered uneconomical and inefficient when planning simple activities. Finally the total float was considered and showed that schedules produced using the walk through had far more leeway allowing the project team to focus on keeping fewer activities on schedule.

The results showed that the walk through visualisation was more beneficial to inexperienced planners in developing correct schedules by avoiding missing relationships and invalid relationships. However using this media also provided benefits to the experienced planners, causing their schedules to have fewer critical activities and improved finishing dates.

The results of this research showed that using 3D visualisation during the planning stages:
- Reduced the number of missing activities
- Reduced the number of missing relationships
- Reduced invalid relationships in the schedule
- Reduced resource fluctuation for complex construction processes

The use of this technology also assisted planners in providing a more reliable and ‘good’ schedule with reduced working times and fewer critical activities. In addition it provided a more level platform for both experienced and inexperienced to generate a schedule.

3.3 Intelligent system for visual simulation of construction projects

3.3.1 Background
This research was the subject of a PhD study carried out by Adjei-Kumi at the University of Strathclyde completed in 1997. The work postulated that existing construction planning software was somewhat inadequate as the evaluation of the schedule was left to the ability of the planner to visualise each phase of construction and consider alternative solutions. The work envisaged the use of virtual reality to overcome this problem and provide a visualisation tool.

3.3.2 Objectives
The research had two main aims. The first was to define and develop a computer-based approach that assisted in the simulation of the construction process both visually and intelligently. This was undertaken by identifying and extracting knowledge on construction processes, utilising these with knowledge based systems and providing visual simulations of construction tasks.

The second aim was to improve communication between all levels of construction personnel ranging from site staff to high-level management staff, by using visualisation techniques.

In order to achieve the above aims, various objectives were defined.

- A demonstration of the potential use of intelligent simulation and visualisation of construction processes.
• A demonstration of the feasibility of knowledge based systems to automate the link between a construction schedule and graphical representations of the objects (4 dimensional planning)

• The development of a library of virtual reality objects to represent various building components (including facilities and temporary works).

• To develop and implement a prototype system which supported the planning stage of construction projects. The system would make use knowledge based systems, virtual reality and existing scheduling tools and methods.

3.3.3 Methodology
To achieve the aims the Virtual Reality PLANNER (VR PLANNER) system was developed. The architecture of this system comprised of three modules:

• A VR application module called PROject VISualisation SYStem (PROVISYS). This module has an embodied VR application, which is responsible for all issues relating to the graphics functions of the system.

• A knowledge based application module called AOTOmated construction PLANning module (AUTOPLAN). This module contains a knowledge-based application, which acts as the co-ordinator of the entire system. From this module all information relating to building components are structured and stored. The module also contains information relating to construction methods and the link between activities and graphical images.

• An existing project planning tool which is responsible for the display of activities and resources in the traditional way. This also allowed the user to make amendments to the schedule.

In addition a Data Base Management System was used. The DBMS supplies the system with data about resources etc. In addition it also provides the Graphical User Interface (GUI) for the system.

The architecture of the VR PLANNER and the incorporated modules can be seen in Figure 3
The graphical interface of PROVISYS allows the user to define the spatial configuration of the building facility. During this process various components of construction can be manipulated by supplying dimensions. Also at this stage on site facilities, such as cabins etc. can be positioned. The building components are selected from the Virtual Library that contains the 3D graphical representation of components, facilities, equipment, events and plant.

The Virtual Library is separated into two sections. The first is the product based graphical model section. This contains components, which do not physically undergo any processing and do not form part of the finished product. These are categorised as Plant, equipment and facilities. The second section is the process based graphical models. The objects in this part of the library represent parts of the project, which undergo some amount of processing and form part of the finished work. This section is split into three sections: visible components, invisible components and events.

Once input through the PROVISYS module, object information, such as geometry, is transferred into AUTOPLAN. Once imported into AUTOPLAN each component or facility can be broken down into activities required for its construction and subsequently appropriate graphical objects are attached to the generated activities. Following this AUTOPLAN determines the work content of each activity or facility and allocates resources for each task. Information relating to the resources is supplied from the DBMS and hence the duration of each task is established. The activities are then placed in sequential order.

The task information from AUTOPLAN is communicated to the project-planning package for activity scheduling and resource analysis. Any manual amendments to the schedule are communicated back to AUTOPLAN. At the end of this stage the

Figure 3: The functional architecture of VR Planner
(Source: Adjei-Kumi, 1997)
data related to activities and their graphical representation are accessed by PROVISYS and simulated in a virtual environment, providing a 4D construction sequence.

Once the prototype had been defined the system was implemented using actual software available. The layout of the system, its relationship to the prototype and the software packages used are shown in Figure 4

![Figure 4: Main components of the VR Planner Prototype](Source Adjei-Kumi, 1997)

The PROVISYS module was developed using Superscape Virtual Reality Toolkit (VRT). Building components can be modelled and manipulated (e.g. duplicated, sized and positioned) using the controls existing within the software. Once the building components had been modelled the data is written to an ASCII file (the product file), which could then be accessed by the AUTOPLAN module.

The AUTOPLAN module is implemented using KAPPA-PC™. This translates the records relating to each building component from the product file and represents them in a knowledge-based structure. Once each component is identified a suitable method of construction is selected. The module then generates the activities and allocates resources necessary for the construction of the building. This information is then written to the sequence file.

The sequence file is a database file created using Borland DBASE V3. This file can then be transferred into Primavera P3 project planning software for any schedule adjustments. Here the schedule can be manipulated in the usual way making use of the tools available is the planning software. Once amended it can be exported into a database file called the schedule file.

The schedule file is transferred to AUTOPLAN and a process file is created. This contains all information about activity start times, duration’s and orders. Using this file
PROVISYS reads this information, relates it to the objects in the building and simulates the construction process through VRT.

3.3.4 Results
The prototype system was tested and evaluated using two hypothetical construction projects. The first was a two-storey concrete frame building using both pre-cast and in-situ concrete. The second project consisted of a single storey building.

For each of the projects, the data relating to the objects within the building were written to a product file. In the AUTOPLAN module the product files were used and information regarding resources and plant etc. were allocated to each of the building components. Once produced by AUTOPLAN the sequence files were transferred to P3 where activities were linked and amended. The resulting schedule file was then transferred back to the AUTOPLAN module and finally to the visualiser, which provided a time elapsed ‘movie’ of the events during construction.

During testing it was found that the construction of the 3D objects was time consuming because of difficulty positioning components accurately in the 3D environment. The AUTOPLAN module assisted with the production of method statements and meant that resources could be attached to operations easily. The work did conclude that the use of P3 software was dependent on the competency of the user.

Due to the case studies being hypothetical there was difficulty in comparing the outputs of the system to real events. In order to attempt to test the ‘realism’ of the system, the results were shown to both academics and engineers who agreed that the output was a true representation of a real project. It was highlighted however, that the number of activities generated for the test cases were very low in comparison to a ‘live’ project.

3.4 Virtual Construction Environment for Project Planning
3.4.1 Background
This research project is currently being embarked upon at Virginia Tech, USA by Ahmed Waly and Walid Thabet. The work utilises both virtual reality technology and decision support systems to create a virtual reality environment where construction projects can be built and rehearsed in virtual reality. From this rehearsal, a construction schedule can be generated.

3.4.2 Objectives
The primary objective of the work is to produce an automated approach to project planning whilst retaining the human planner fully responsible for all of the decision-making. The tool is based in a virtual reality environment allowing the planner to visualise and build construction projects in a near reality sense. The research has identified that previous work has been concentrated into 3 main areas. The first area uses artificial intelligence and knowledge based systems to automate the project planning process. The second area relates to 4D tools that enable visualisation of the planning process, and the third area represents a combination of these.
3.4.3 Methodology
The research is developing a framework based on virtual reality technologies to provide an interactive environment for visualising construction projects. The environment allows the planner to construct and re-construct graphical elements of a 3D product model providing a rehearsal of the construction sequence. The movements of the user when constructing the model are captured and processed in order to develop planning sequences. Support modules within the system provide generic construction data and perform the analysis and computations.

Two forms of support module are present within the system, Information Processing Assistants (IPA’s) and Analysis Modules. Whilst constructing the 3D model in the perceived order of construction tasks, the user can also make decisions about methods used to complete the activity using the IPA’s.

The IPA’s contain generic data about means, methods and procedures to assist the user during the allocation of resources and the extracting of information about the resources. The IPA’s get the commands from the user, process the information and provide information back to the user.

The analysis modules are used to perform analysis and computations for each of the tasks once the resources and sequences have been specified, for example the calculation of the duration for each task associated with an object.
3.4.4 Results
This project is currently ongoing at Virginia Tech, and as yet has not been validated against a real life scenario. The prototype is still in the development stages and results thus far are limited to those obtained through testing the modules in hypothetical situations. The results however do report that during the ‘virtual’ construction the planner will be able to visually depict some spatial conflicts. It is envisaged that these will be mainly for major operations for example locating cranes or other large plant around the site.

3.5 A Virtual Environment for modular building construction
3.5.1 Background
Murray, Fernando and Aouad at Salford University are currently undertaking a project investigating the use of a virtual environment for simulating building construction. This is being developed as part of the FutureHome project supported by the EU Brite / Euram award. The FutureHome project is a 3-year, 5 million Euro EU funded project containing 15 partners in 6 European countries, forming part of a global project under the Intelligent Manufacturing Systems programme. The aim of this project is to
enable house construction to be improved by utilising advanced manufacturing systems and techniques.

3.5.2 Project aims
The aim of the project is to develop a prototype virtual environment that allows a model of a house to be constructed from a library of prefabricated components defined within the FutureHome Project.

A second aim of the prototype system is to use constraint recognition techniques to automatically detect whether the user manipulated components can be linked together. In addition a database holds information relating to the types of components that are used within the building.

3.5.3 Methodology
The prototype system has two constituent parts: a 3D building design environment and a construction database.

Within the 3D environment, the user is able to navigate the building components and view them in detail. The components can be selected from a standard library which is viewed using an interactive menu. Once a basic component has been selected (for example door, window, wall etc.) the user is presented with a next level menu of further/ specific component types. Once a component is selected it can be manipulated i.e. rotations and translations can be applied, and positioned in the environment. The system provides a collision detection facility that highlights colliding objects to the user when they are being positioned. Once the parts are aligned in their approximate position, the system snaps the objects together. As each component is added to the building, information relating to the component is stored in the database.

The IFC compliant construction database manages all of the information relating to the construction of the components. It stores information regarding the construction of the component, for example the methods of construction. This is also responsible for storing information relating to the resources, materials and deliveries to the site.

Once the building is complete, the construction process can be simulated as a 4D animated movie using the information stored in the database. In addition to this, the schedule (generated using the recorded process and database information) can be exported to a scheduling software package. This can be amended in the scheduling software and imported back into the virtual environment.
3.5.4 Results
This research is ongoing at Salford University. It is envisaged that future work will further develop the tool and assist the construction of housing in Europe. It is also envisaged that the tool will assist with the maintenance of a building as it can be used as a reference tool. Instead of providing the building owners or facility managers with ‘as constructed’ drawings, FutureHome will provide an adaptable 3D model. Other projected developments will allow the 3D interface to be utilised in a CAVE environment and for a cost-oriented model of the assembly processes to be integrated into the system. This will provide a continuation of the OSCON project as discussed in section 3.7

3.6 Simulation in Construction
3.6.1 Background
Construction project simulation is an area of ongoing investigation at Purdue University, USA. The simulation is based upon the CYCLONE (CYClic Operations NEtwork) software, developed by Daniel Haplin at the University of Illinois in 1973. The Cyclone software uses a modelling technique that allows the graphical representation and simulation of construction processes.
3.6.2 Objectives
Since the initial development of the CYCLONE system, other work has been carried out to improve the system. Based on the theory that modelling construction processes can be beneficial, the aim of the CYCLONE system is to provide a simplified simulation of the modelling process, which could be accessible to construction practitioners.

In order to further enhance the system research was carried out that provided the ability to model resource sharing. It was acknowledged that resources on site can be shared amongst various construction processes being carried out simultaneously. In addition, the modelling of the interdependence of processes was explored, as the completion of one or more processes can effect the start time of other processes occurring on the site.

3.6.3 Methodology
The basic CYCLONE system provides a framework from which multiple processes, occurring on the construction site, can be simulated. This simulation is undertaken by carrying out four basic steps:

- Identifying all of the processes that are to be modelled for the construction of the facility
- Identifying and defining each of the resources to be used for each of the processes/tasks
- Developing process models using the modelling elements within the cyclone system
- Undertaking the simulation of each of the processes identified using the resources specified

In order to advance this concept, two further steps were included. The first provided the ability to model common resources i.e. resources that are used for more than one task, and the second provided the ability to model the interdependencies between the various processes i.e. the links between tasks.

To model common resources, all resources were included in a resource pool. This pool stores information relating to the amount and type of resource available to the project as a whole. Resources are either modelled as common or shared and these are then linked to either one or more processes. In order to ensure that correct assignments are provided to the process, priority can be given to the allocation of the resource.

On the construction site a process can have one or more successors and these successors could relate to one or more further processes in the simulation model. Functionality was added to CYCLONE to provide the ability to determine when a required quantity of a process had been completed. Using this functionality the modeller could specify either a relationship where a successor starts after whole completion of the predecessor or the successor starts after partial completion of the predecessor at a specified point.
3.6.4 Results
In order to test the updated CYCLONE system, a case study was carried out to complete the simulation of a bridge construction. Using the system process models were developed for each stage of one section of the construction. Initially an overall model for pier construction was developed and from this each process was modelled in detail. This provided a detailed model that included the resources used at each stage and the dependencies of each task relating to its predecessor and successor.

3.7 Open Systems for Construction
3.7.1 Background
The Open Systems for Construction (OSCON) project was carried out at the University of Salford between April 1995 and March 1997. By Ghassan Aouad, the DOE funded project aimed to build on the results of the preceding ICON project and produce a prototype software application that assisted in the area of construction project management.

3.7.2 Project Aims and objectives
The main aim of the project was to illustrate the benefits of using a centralised database as a means of integrating the information used by a number of participants within the construction project. This would enable easier scheduling, cost estimating and visualisation of construction projects.

In order to achieve this aim, the project had several objectives including the development of demonstrators for applications such as architectural design, cost estimating and planning which would all be integrated into a central database. A further objective was the use of commercial software such as AutoCAD, SuperProject and Netscape along with an object oriented database to allow the sharing of information and produce a user-friendly interface.

3.7.3 Methodology
In order to provide an integrated approach, a suite of software applications were used to share information via a central object oriented database. These included a CAD application; cost estimating software, construction scheduling software and a VRML interface. Within the CAD application the user has the ability to create and manipulate components that could then be stored in the central database. The VRML interface reads this information from the database and displays the components in 3D allowing real-time navigation of the building. Based on the design information stored in the database, the cost estimate and planning modules generate costing and schedule information for each component. The overall architecture of the OSCON system is shown in Figure 7
A steering group of industrial partners was used to gather the knowledge required to design each of the models.

The planning application module of the OSCON system utilises CA-SuperProject software. Once the construction operations are identified and stored in the central database, they are imported into CA-SuperProject Along with activity durations and resources. No links between tasks or operations are defined however; these are left to the user to manipulate within the schedule.

3.7.4 Results
The OSCON project produced a prototype system that integrated various aspects of the construction cycle. This demonstrated the use of an integrated database to show that communication could be improved. This in turn resulted in increased productivity. The system also demonstrated that commercially available software packages could be used with the system to reduce the initial outlay cost.

OSCON used knowledge stored in a database to link information relating to CAD objects to a project schedule. Using a case study supplied from one of the OSCON collaborators, testing was undertaken. A four-bedroom bungalow construction was implemented in OSCON and from this estimations of cost were established using a resource-based technique. In addition to this a schedule of tasks was generated using the planning module and the building was viewed in 3D using the virtual reality viewer. This simulation was deemed to be successful by both construction professionals and academics.
3.8 CONPLAN: construction planning and buildability evaluation in an integrated and intelligent construction environment
3.8.1 Background
Hassan undertook this PhD study in 1997 at Salford University. The work presents the development of the prototype application for Construction Planning and Design Analysis (CONPLAN).

CONPLAN forms an integral part of the Simultaneous Prototyping for An integrated Construction Environment (SPACE) project developed at Salford University. SPACE provides a rapid prototyping environment to develop an intelligent integrated design and construction system for the civil and building domain. At the centre of SPACE is a project model from which all integrated applications can obtain data. This model represents data that is independent of any application. It defines entities that describe the building components as well as the relationship between them. SPACE supports a range of applications that can be used throughout the life cycle of a construction project. This includes design, space recognition, element specification, construction planning, site layout planning, estimating, valuation, maintenance and visualisation using a virtual reality interface (Faraj and Alshawi, 1999).

3.8.2 Objectives
As described, construction planning is an integral part of the SPACE environment. The aim of the system was to generate construction schedules based on required activities and resources. This schedule could then be analysed to identify buildability or constructability problems. In order to develop the prototype system and achieve the aims, the research identified 4 key objectives.

- Analysis of the construction planning process to establish the information required when producing a construction plan. Information obtained from the planning stage used to evaluate the constructability was also identified.

- The undertaking of an object oriented analysis to produce a conceptual model for an integrated environment. This would include an information model representing planning information and a process model of the planning process.

- The development of a knowledge based system that could be integrated with other applications in the SPACE environment. This could then be incorporated into the SPACE environment.

- Testing of the planning prototype would be undertaken to assess the validity and usefulness.

3.8.3 Methodology
The architecture of the CONPLAN system consists of several external applications along with a central knowledge based system. Information is input into CONPLAN via a graphical user interface. Following this, design information is processed into a building product model using the CAPE module (CheWanPutra, 1997) of the SPACE system. The graphical interface also facilitates output information providing visual simulation of the construction. CA-SuperProject project management software is used to display the construction plans. Information pertaining to the resources for the project is stored in database format via DBASE software.
Within CONPLAN there also exists a knowledge base, implemented in KAPPA-PC. This module contains design information, construction knowledge and various processes required to generate the construction plan, and hence carry out the buildability analysis. The overall architecture of the CONPLAN system can be seen in Figure 8.

The input of the CONPLAN system is separated into three sections. Information relating to the design is input through the graphical interface via AutoCAD and AutoCAD AEC. This is communicated as a series of object oriented building elements. The second source of input is obtained from external databases holding information relating to resources i.e. productivity, availability, cost etc. The final source of input is from the project management system. This provides feedback regarding specific activities, for example duration, start/finish dates etc. This feedback information is provided once the software has generated an initial program.

The knowledge-based system within CONPLAN consists of three processes.

Collating design information and construction methods – This is carried out through a building module in the system. Construction methods and resources and selected from external databases.

Developing construction plans – Using the collated design information and construction methods, a construction schedule is generated using the scheduling software. The design elements are converted into activities, which are then decomposed further to produce a more complete schedule.
Buildability evaluation – Using the compiled schedule CONPLAN performs a buildability analysis. This is based on the building elements specification, repetitiveness, assembly etc.

Once the three stages above are complete, the results are displayed to the user through the graphical user interface. The project management software provides the user with a construction schedule for the project. The buildability results are displayed through the graphical interface using a line graph and a visualisation of the construction is provided via a virtual reality model using World Tool Kit’s virtual reality modelling software.

3.8.4 Results
To validate the approach and applicability of CONPLAN, data was used from a completed construction project. The testing and validation was carried out in two stages. The first stage analysed the construction schedule generated and the second evaluated the buildability analysis. To provide feedback on the system, comments were taken from field practitioners, academics and researchers. Overall the results showed that CONPLAN provided an effective tool for the generation of a construction plan and the analysis of the buildability of a project.

There were however, areas where it was considered CONPLAN could be improved. For example the user could be given more control to amend the construction schedule and more options to decide construction methods could be provided. In addition the database could be extended to include more plant and facilities.

3.9 VTT Finland, Construction IT Research projects
3.9.1 Background
The Applications of Virtual Reality for Building Construction Delivery (VIRIL) is an ongoing project at VTT. VIRIL is a research and development project investigating the applications of Virtual Reality Technology for Building Construction Delivery. The mission of VIRIL is to provide knowledge for the practical applications of virtual reality to live construction projects. The project is being undertaken in conjunction with VTT and various other partners including Finnish companies, The University of Strathclyde and Stanford University.

3.9.2 Objectives
The main aim of VIRIL is to gain an understanding of possibilities and cost / benefit ratios of Virtual Reality for industrial applications. The main objective of VIRIL is the development of prototypes and demonstrators of virtual reality applications for industrial applications.

The research is focusing on the modelling and simulation of construction processes using VR technology, VR models of buildings, 3D Presentation Technology and Telepresence.

3.9.3 Methodology
A 4D modelling approach was implemented using a pilot project of an eight-floor office building for the YIT Corporation in Helsinki. Source data was provided by the YIT Corporation and the 4D model was generated at the Virtual Construction
Simulation Research Group (VCSRG) at Strathclyde University using some of the technology described in section 3.3

Implemented through Superscape Virtual Reality Toolkit software the project is a simulation of the daily workload on the construction site. The simulation can be stepped through, at daily intervals. In addition, a particular day can be selected during the construction period to view progress up to that day. The ability is also present to move plant around the site.

3.9.4 ProMoTe
VTT-ProMoTe is an EXPRESS Schema and STEP data browser.

The Data browser enables viewing of STEP product data as an entity hierarchy and as a data content hierarchy based tree. The software supports access to distributed models over the Internet. A further feature is creation of virtual reality models, which can be used as a 3D user interface to product models and related documents over the Internet. Links from instances to documents are also supported.

3.10 Design Build Knowledge Information Slider System (DBKISS)
3.10.1 Background
Renate Fruchter and Helmut Krawinkler undertook this recently completed research at Stanford University. The work identified that computer-based representation, capture, linking, visualization, navigation, and use of the information and knowledge created in a multi-disciplinary project environment remained a difficult problem.

3.10.2 Methodology
The DB KISS project proposed to develop methods and a prototype for knowledge management and navigation of information that constitutes a design-build project memory. The research proposed a product-based, context-based, Web-mediated approach for project, product, and process evolution capture, organization, and navigation. This would be achieved by formalising and articulating the link between four network levels:

- People network
- Design informal knowledge network
- Design and construction formal knowledge network
- Construction site knowledge network

In assisting the sharing of information, the system enabled any parties involved in construction to seamlessly slide among the different network levels. This allowed them to retrieve and re-use knowledge and information in the decision support process.

3.11 Virtual Construction (VIRCON) – Australia
3.11.1 Background
Work has recently been undertaken at the University of Sydney to investigate the development of an integrated system to assist the planning and visualisation of construction schedules. Utilising existing software packages, the system was aimed at assisting both existing planners in the Australian construction industry. It also aimed to assist students who were training to become planners without the need to
plan live projects whilst waiting for the site works to commence before experiencing constructability problems.

3.11.2 Objectives
VIRCON was developed as both a planning and teaching tool. In order to achieve the desired effect for both aspirations the following aims were established:

- The system would be interactive, enabling scheduling information to be manipulated during the construction phase.
- To assist in the teaching aspect, the system would be able to run case projects, which could then act as the basis for setting student exercises.
- To provide remote access to the system via the Internet, thus enabling planning fundamentals to be learned.
- The system would make use of existing commercially available software in addition to developing new prototype software.
- Allow the sharing and integration of information between each of the team members within the construction project.

3.11.3 Methodology
The VIRCON system is comprised of two main modules, the Construction Management Information system (CMIS) and the Visualisation module.

The CMIS module of the VIRCON system is an object oriented Windows based program written in Visual C++. This module provides the user interface for the inputting of data in addition to the analysis and reporting of information. Once information has been input into the CMIS, it is automatically stored in an object-oriented database. In addition to undertaking time management and scheduling, CMIS also provides the capability to process other information such as cost management, resource management, risk management and cash flow analysis. Each of the processing functions were designed as separate program modules contained within a dynamic library, each linked to the project database. This enables the programs to access the same data sets and exchange information amongst themselves.

The second module contained within the VIRCON system provides the ability to generate simulations of the construction schedule using a 3D CAD model and construction planning data from the CMIS. The visualisation module provides schedule simulator and 3D Walkthrough tools for the VIRCON system. The schedule simulator utilises the existing AutoCAD Release 14 ObjectARX Application Programming Interface. Prior to the start of the simulation, the 3D CAD model of the project is broken down into the constituent components, with each of the objects relating to activities on the construction schedule. Once this has been undertaken, a link is established between the 3D object and the corresponding activity, this can be done either manually or automatically. Once these are linked a simulation can be generated using the combined information.
3.12 A Virtual Reality System for Site Layout Planning

3.12.1 Background
Reported in 1997, work has been undertaken at the University of Liverpool, UK to investigate the use of Virtual Reality to assist in the area of site layout planning. Lead by Dr Halim Boussabaine, the investigation aimed at exploring the possibilities of improving the site planning process and assisting planners using virtual reality techniques.

3.12.2 Objectives
The main aim of this research was to demonstrate the feasibility of virtual reality for the assistance of the site layout element of the construction-planning phase. Once a virtual reality model was developed the planner would possess the ability to move around the site before construction started whilst efficiently locating required facilities. Additionally, the planner would be able to devise a safe and efficient site and identify potential health and safety problems prior to construction. In order to achieve this the objective of the task was the generation of a prototype construction site layout using virtual reality software.

3.12.3 Methodology
In order to test the objectives a virtual reality model was generated using the Virtual Reality Toolkit (VRT) developed by Superscape. A model of an existing construction site located in Liverpool, UK was used to generate virtual reality objects. Objects were generated using the shape editing functions contained within the Superscape software and these were loaded into the virtual world.

Once the world had been created, it was possible to generate static viewpoints of the site allow the user of the software to walk through the site layout in real time. Objects already generated and positioned in the world could be easily moved around within the extents of the site by utilising a drag and drop principal. The various objects could also be accurately positioned by utilising the position tools contained within the software.

3.12.4 Results
Whilst the work succeeded in the aim of demonstrating that virtual reality could be utilised for the planning of site layouts, little difference exists between the underlying principles of the work and the current tasks undertaken by planners during the site-planning phase.

Using the principles undertaken in this research, the virtual reality objects representing site facilities have to be generated and positioned manually by the planner in a similar way that paper templates are currently used. Whilst this process is similar, utilising virtual reality does then allow the planner to peruse the site both in real time and in 3 dimensions allowing for greater comprehension.
3.13 Discussions and Summary

This section demonstrates that simulation and visualisation techniques can greatly assist the project planning process. This is a major area of research both in the UK and overseas. 4D models allow the viewing of the project once a schedule is compiled. However, it is apparent from the work by Songer that using 3D visualisation of a completed building can greatly assist in the comprehension of tasks required by the planners. The CYCLONE system on the other hand provides evidence that modelling the processes required to ‘build a building’ is beneficial in providing a logistical plan of the operations required in order to complete the construction.

The focus of a large body of the research efforts is 4D CAD. Work currently being undertaken at Stanford University is exploiting this 4D technology and discovering new ways in which this can be utilised. The work by McKinney-Liston aims to add new functionality to the 4D model by providing annotations. These annotations will mean the 4D simulations not only depict the schedule visually but also provide an explanation of how the building components fit together. 4D is also being used in other fields to assist in costing issues, in addition being used to assist the construction of a live project.

The VR PLANNER system further builds on the 4D philosophy by adding basic intelligence to the planning process. Fundamental 4D CAD is a tool for review, as the construction schedule has to be generated before a simulation can take place. The VR PLANNER utilises a knowledge base to take inputted building components and break them down into constituent parts and tasks. Following this the system assigns resources to the task from the knowledge based AUTOPLAN module and calculates the temporal requirements for the activity. Although the system moves one stage further and assists with the initial production of the schedule, its applicability to all construction forms could be limited. No ‘real life’ testing was carried out of the system and so it cannot be concluded whether the system worked well for all aspects of the construction process. Although the system did provide a warehouse of objects and processes, these would need to be expanded to provide a fully comprehensive library including activity space requirements.

The virtual environment for modular building construction has similar disadvantages. The system provides the user with 3D objects, which can be manipulated through a virtual environment to form a house. Each of the objects has inherent information relating to connections and resources required for its construction. Subsequently a schedule is generated and a 4D simulation produced. Again this ‘library’ is only suitable for the construction of these particular facilities and a far more exhaustive library is required to apply this to other construction projects.

VRPLANNER and the Modular Housing System attempt to replace the planner by utilising knowledge, however the Virtual Environment for project planning retains the construction planner at the centre of the process. Utilising visualisation techniques and supporting modules, a simulation is constructed. The planner constructs the building elements in the perceived order of construction and provides information relating to the method of construction. The support modules contain resource
information and the construction time for each element. This information is collated to provide the 4D simulation.

OSCON uses a product model as its central core and information is passed from this to the planning application. The central database holds information relating to construction operations and resources. This is then passed to the planning software. The user is left to manipulate the schedule and once completed, this information is passed back to the database to implement through CAD or a virtual reality viewer.

CONPLAN also relies on a central core of information. As an integral part of the SPACE system, CONPLAN uses other applications linked to SPACE to provide information relating to various components. Using the CONPLAN knowledge base, the design elements are decomposed into construction activities from which a schedule is generated. This information is passed back into the central database and can be viewed through a further SPACE application.

Each of these projects has demonstrated that visualisation of the schedule can benefit the planning process. Some use an already generated schedule as temporal input that is then linked to VR or CAD objects. Others use knowledge to generate an analysis of the schedule thus providing an expert system rather than a support tool. The absence of space required to undertake construction is a factor missing from all of the above systems. Each of the systems links a constructed object or component with a task but take no account of the space required to fulfil the task. This technique highlights conflicts between two components during or after the construction however, the period during task execution requires elaboration to define the space being occupied.
4.0 SPACE REQUIREMENTS FOR CONSTRUCTION

Simulating the construction process provides the construction planner with the ability to detect incorrect schedule logic and highlight potential conflicts between building elements. It has been acknowledged however, that space use on the construction site is a key element in the completion of a successful project. Effectively planning the use of space during the construction phase can assist in efficient work activities. This section of the report reviews this topic illustrating an area of ongoing research that provides systems and methods to improve site layout planning processes and incorporate activity space requirements.

4.1 SightPlan

4.1.1 Background

Initially developed by Tommelein as a PhD study at Stanford University, SightPlan is an expert system for designing construction site layouts. Since then various publications have been presented relating to the topic and it has formed the basis of the work currently being undertaken at the University of Berkley under the direction of Tommelein.

4.1.2 Objectives

In order to achieve the aim of producing an expert system to design site layouts, the research had four main objectives.

The first objective was to investigate the type of knowledge used by construction managers when designing a site layout. This would include general ‘rules of thumb’ and various methods used by managers when beginning the process of layout generation. The second objective set was the construction of a model that would mimic the actions taken when generating a site layout. This would include an investigation of information (both written and from the field) that could be compiled to model the processes used by planners. The third objective of the work was the testing of blackboard architecture i.e. the expert system technology for representing multiple modular knowledge sources, on a realistic design problem. This would assess the use of blackboard architecture for the design of an expert system to model construction tasks. The final objective was the identification of the possibilities for interaction between the SightPlan computer model and construction managers who generate site layouts.

4.1.3 Methodology

The knowledge contained within SightPlan was obtained from undertaking two case studies. The first was the Intermountain Power Plant. From undertaking a layout protocol analysis of the site a model was generated and this became the basis for the SightPlan model. A further case study of the American 1 Power Plant was used to validate and provide extensions to the model.

Both the architect-engineers and the construction managers for the power plant generated a site layout design as required for their specific task. The steps followed by these became the basis of the SightPlan model. The architect engineers produced a layout which showed not only the permanent facilities on the site, (such as the constructed buildings), but also temporary structures such as warehouses, office buildings and parking areas. In addition to these they also estimated the need for
material storage areas. Once completed, a layout drawing and milestone dates were passed to the construction managers.

The construction manager’s task was to determine the layout of the material storage areas for 25 major contractors. From the layout drawing provided by the architect-engineers, all areas occupied with permanent works were identified along with other areas that could not be utilised. Using this information and the anticipated storage areas produced by the architect-engineers, the construction managers were able to identify areas that could be used for long-term material storage. For each of the 25 contractors, the construction manager identified the required area, access requirements and how critical their activity was. Based on this information the areas were ranked by importance and the most important area was positioned first. This information was modelled as processes that could be used as the basis of SightPlan.

In order for SightPlan to function effectively, it requires two forms of knowledge. Firstly it must know which objects are to be positioned and any constraints applied to them; secondly it must have a strategy for positioning the objects. Information pertaining to the objects and constraints are input into SightPlan such as:

- Major permanent facilities and dimensions
- Access roads and dimensions
- Long-term temporary facilities
- Long-term storage areas
- Constraints on the location of temporary facilities and storage areas
- Zones which partition the site

The strategy input into SightPlan is based on the process learned from the architect-engineers and the construction managers. In summary:

- The space occupied by permanent and temporary facilities should be established.
- The space occupied by short-term temporary facilities should be identified.
- Larger objects should be positioned first.

SightPlan follows the sequence described above by firstly carrying out the architect-engineers layout. In order to fulfil this, SightPlan creates an initial arrangement and defines the boundaries of the site. Following this SightPlan includes fixed objects into the arrangement. The system then identifies facilities that can be grouped together and determines the dimensions of these groups. These groups are positioned sequentially using constraints on location and size. Once this layout is complete, it is used as input for the construction manager layout, mirroring the real life process.

Facilities on the architect-engineer layout are deemed as fixed. From this, the construction manager module creates a new arrangement. This includes site boundaries and what are considered to be ‘permanent’ fixtures. The system then positions each storage area sequentially using the constraints used by the construction manager in the actual layout design. SightPlan stops when no more executable actions remain and it has computed locations for all of the facilities requiring space.
4.1.4 Results
Using SightPlan, the production of a site layout for the power plant demonstrated the ability for a computer program to imitate the steps undertaken by construction planners. The model takes into account more factors than previous methods, for example the classification of objects by type, the spatial and temporal characteristics of the objects and the constraints placed on an object.

Using the second case study the model underlying the SightPlan system was further tested. From this is was proved that the underlying strategy i.e. the one relating to the power plant was quite general as it could be used for the generation of layouts for other sites. This study did show however, new objects and constraints relating to the objects had to be specified independently. One disadvantage identified was the inability of the system to out perform the traditional methods in terms of speed of production of a layout. It was reported that construction professionals compiled a layout for the power plant in less than one day. SightPlan required over three hours to complete the layout with less detailed input.

4.2 MoveCapPlan
4.2.1 Background
Under the direction of Tommelein, various research relating to space scheduling on construction sites has been undertaken at the Department of Civil and Environmental Engineering, University of California at Berkeley. The work focuses on the scheduling of material space on the construction site.

4.2.2 Objectives
The MoveCapPlan system was developed to provide an integrated environment, which aids the modelling of the movement of materials. The system also assists the capture of material storage locations and the planning of material rehandling throughout the construction process. The system is an integration of two modules, MovePlan and CAPSY™. The main objective of MovePlan is to assist in planning the reuse of site space over time, whilst CAPSY is a one-person portable surveying station.

4.2.3 Methodology
The MovePlan system assists the planning of the location of materials on site. The module links a CPM schedule of activities for construction, with a two dimensional graphical interface used to represent the use of space over time. The user is required to input the CPM activity schedule and materials required, along with space required by each material. The user then selects a time period over which to construct a site layout. MovePlan displays a current site layout showing materials already in place, along with templates to represent materials to be located for the time period. The materials to be located are deduced from the CPM schedule of activities. The material templates are then positioned on the site plan until a satisfactory layout is obtained. Areas depicting materials that have the location fixed by the user, or were positioned in a layout including or overlapping the current time interval cannot be moved. The layout sequence can be played back to show how the site evolves over time.
CAPSY™ is a real time positioning system, which makes possible the logging of materials on site and the tracing of worker pathways or equipment trajectories. Once calibrated, the system uses beacons located around the site to triangulate its position. The locations obtained from the system can be uploaded into the MovePlan system and the difference between planned and actual site layouts can be calculated.

4.2.4 Results
Various applications of the MoveCapPlan system have been identified. The system could assist in the developing and communicating of dynamic layout information. This could be used to negotiate the use of work areas and coordinate shared resources. The possibility also exists for the templates to store attributes such as material information. The CAPSY aspect of the system makes it possible for the layout plan to be updated regularly. When this is integrated with an inventory control system it becomes easy to check materials that are in short supply. In addition each of the templates can have embedded knowledge to highlight potential problems. For example, a space template for underground utilities could determine whether above ground resources could overlap. The flow of materials on the site can be modelled as each area can be labelled as laydown, staging, assembly, installation or waste. Using this information the material flow can be assessed. Finally the system can be used for data collection to facilitate the heuristics for the estimation of material space requirements.

4.3 Virtual Construction Materials Router
4.3.1 Background
This work is currently the subject of a PhD project being undertaken by Yang at the University of Wolverhampton, UK. The work has identified that the reliable prediction of materials routing is critical for optimum site management. Work has been carried out investigating the position of materials within the construction site, however the area of material routing is relatively untouched. This work proposes to utilise virtual reality technology and Geographic Information Systems (GIS) to assist in the area of material routing.
4.3.2 Objectives
The main aim of the project is the production of a virtual reality based software system, The Virtual Construction Materials Router (VCMR). This is to be a new approach to assist site planners in the prediction, monitoring and management of material routing. The prototype will have the ability to generate various scenarios for material routing and allow the rehearsal of these scenarios as the construction work progresses. This will enable the user to select the most suitable route for the movement of the material.

In order to achieve the aim, the work has specified various objectives. Firstly the work identifies the main factors affecting the routing of material resources within the confines of the construction site. Once these factors are identified the work will progress to develop a knowledge framework / model which supports the decision making process of determining the route. From the model, a prototype system will be developed using a knowledge base and a GIS based CAD system to produce the most suitable movement routes. Finally the system will be tested on a live project scenario in order to assess the validity of the model and the prototype.

4.3.3 Methodology
The prototype system consists of the following components; a CAD/GIS module, a database management module and a fuzzy logic decision module. An additional module provides the user with a visualisation of the decisions made in a virtual reality interface. Figure 10 displays the interaction of each of the modules within the VCMR system.

![Figure 10: Data Flow in the VCMR](Source: Yang, 2000)

The CAD module of the system utilises AutoCAD Map software and is used for the initial input of the site information. This information includes location of ‘to be constructed’ facilities, storage areas and access / egress points. Any spatial
constraints within each of the positioned areas are recorded using the functions inherent within the AutoCAD Map software. Once the geometric properties and constraints are specified, they are exported into database format. This file is then stored in the database management module, implemented in Microsoft Access. As work progresses on the site, the thematic data relating to the spatial attributes of materials can be updated through the CAD module and in the database.

Once imported into the database, the relevant data is transferred into the decision module implemented using the FuzyTECH software. Fuzzy logic was used as it provides no hard yes / no rules but uses input from the database (including site geometry, scheduling of activities and spatial constraints) to apply a numeric value. This can be used to quantify the output, providing varying levels of demand for the material.

The decisions from the fuzzy logic module are processed into the database and using Visual Basic (VB) and the Structured Query Language (SQL), a new table is generated detailing the results. This information can be displayed to depict the resulting decisions in graphical format through the CAD module. This enables conflicts between differing routes to be identified graphically.

4.3.4 Results
Presently this work is under validation and is being tested on two major construction sites within the UK. The validation at both of the sites will use data collated from previous layouts where problems with the routing of materials have occurred and been solved. The VCMR will receive the initial input and create new routes to assess whether these would have been applicable in the situation. In addition to this, further testing will be carried out on sites for phases where construction has not yet commenced. These results will be compared to those actually recorded once construction begins.

4.4 4D space planning for Construction Work Spaces
4.4.1 Background
As discussed in section 5.1 work was carried out by David Riley at Penn State University to investigate the use of space on the construction site. This work is continuing into the area of construction space planning at The University of Washington. Here, one of the areas of investigation is the use of 4D models in the development and analysis of construction workspaces.

4.4.2 Objectives
The aim of this work centred on the inclusion of actual physical workspaces, storage areas and paths into a 4D analysis. The work aims to provide an extension to the 4D construction method modeller (described in section 3.1) by including workspaces at an equal level of detail to the components of the constructed building. These spaces would be represented as 3 dimensional objects in a similar way to the actual physical components of the construction facility, having both spatial and temporal attributes.

In order to achieve this, the project defined attributes and properties for the modelling of the various types of construction space required and how these are linked to the 4D model.
4.4.3 Methodology
The work identifies four types of space required in order to undertake a construction task, i.e. the space in which the work task is executed, storage areas, route paths and access points. In order to define the properties of each of these types of space further definitions are proposed. These are the physical property i.e. the size and location of the space, the temporal property i.e. when the space will be required according to the project schedule and inherited properties i.e. the association between the space and the component for which it is being utilised.

The physical property of the space defines not only the size of the space in 3 dimensions, but also the position of the space in relation to component being constructed. In addition to this the physical property also describes information relating to the density of the space. In order to represent the density a numerical value is assigned between 0.1 and 1.0. This describes the ability of the space to share with other space objects.

The temporal properties of each of the space objects provide information about when each of the spaces will be occurring i.e. when it will be active. This active or inactive status is directly related to the component objects and the tasks identified in the construction schedule. However, in order to fully represent how the spaces are used the dates may vary from those of the associated task on the schedule. For example the clean up time once a component is installed may extend past the finish date on the schedule. The storage spaces identified would be active from the dates materials are delivered until the respective activity is completed.

Inherited properties of spaces include the object name within the product model to which the space relates and an activity that relates the space to a defined task on the schedule.

The work assumes that conflicts will only be identified between spaces required for different activities. Any conflicts that occur between spaces required for the undertaking of the same activity are to be resolved by the foreman.

The work also suggests that the level of detail of the planning process has an effect on the development on a realistic 4D model. The planning interval, space usage, activity type and the work zone have an effect on the planning process and hence the usefulness of the derived 4D model. The planning interval represents the time span at which 4D models are generated and analysed to check for time-space conflicts. The space usage represents the space used by various aspects relating to the construction. For example the modelling of a small space relating to a component that only occurred for a very small amount of time would be insignificant. The work also suggests the type of activity being modelled may not benefit from a 4D space model, as physical constraints may have a more deciding factor rather then space.

4.4.4 Results
Using the above attributes and space properties whilst referring to the level of detail required, the work recommended that the modelling of 4D construction operations be focused on HVAC, Electrical, Plumbing, Fire Protection, Carpentry and Curtain Wall operations. On a test case these 6 operations were modelled in 4D and various sequencing alternatives could be evaluated.
4.5 Space Constrained and Resource Constrained Scheduling System (SCaRC)

4.5.1 Background
Undertaken as a PhD research investigation, the development of the SCaRC system was undertaken by Walid Thabet at Virginia Polytechnic Institute. The work identified that whilst previous intelligent scheduling systems had addressed the effects of temporal and resource issues on the construction sequence, none had investigated the effects of spatial constraints that existed within the construction site.

4.5.2 Objectives
The aim of the research was to develop a system that provided the ability to assess the spatial constraints that existed within the construction schedule and take these into account. The system is designed for usage to assist the scheduling of space utilisation on repetitive floors in the construction of multi storey buildings.

4.5.3 Methodology
The scheduling knowledge of SCaRC uses four different types of data about different constraints to generate the schedules, namely horizontal construction logic constraints, vertical construction logic constraints, resource constraints and space constraints. The scheduling of any activity is performed in two consecutive stages, a resource based scheduling stage and a space based scheduling stage. In each specific constraints are considered.

During the resource based scheduling stage the horizontal and vertical construction logic and resource constraints are checked. Firstly the horizontal and vertical constraints are checked ensuring that they are satisfactory to all other floors of the activity segment. Duration rules can be used at this stage to manipulate the initial activity duration defined by the user by increasing or decreasing production rate. If the manipulation of the rate does not succeed in satisfying the constraints, the segment start date is delayed. If the horizontal and vertical constraints are satisfactory, then the resource constraints are checked. During this stage the resource demand to availability is checked. Resource modification rules are incorporated should any changes be made to the production rates in the previous phase. If the demand exceeds the availability the activity start date is delayed.

The second stage of the system undertakes space based scheduling. In this phase the demand for space is compared against the space availability for selected work areas. The activity space required is dependant on both labour and equipment space and this is calculated in accordance with any changes made in the schedule during the resource based scheduling stage. The space required for materials is calculated at data input stage as this is unaffected by changes in the activity duration. The work areas within the building are defined as space blocks and the generated activities are allocated to space blocks during the data input stage. The user defines the space available in each block.

To identify the effect of the available space on the activity, SCaRC uses the space capacity factor (SCF) to measure the ratio between space demand and availability. This is based on the concept that due to congestion within an activity execution space, the start of the activity need not be delayed but the productivity can be recalculated to provide more realistic activity durations. To quantify the decrease in
productivity rate due to limited workspace the degree of congestion or SCF can be calculated using the following formulae:

\[
\text{Space Capacity Factor (SCF)} = \frac{\text{Space Available for Activity}}{\text{Current Space Availability}}
\]

The space capacity factor can be plotted against different productivity rates for construction activities. Figure 11 shows a hypothetical productivity-SCF curve. This shows that when workspace demand is less than available space the productivity remains unaffected. These curves are however hypothetical and require development utilising real world data.

![Productivity - SCF Relationship](source: Thabet and Beliveau, 1994)

The SCaRC system is comprised of three components; a database, schemata structures and knowledge modules. The database provides the graphical user interface for the system allowing the inputting of scheduling data and the viewing of the schedule results. The database is separated into six file containing global space data, activity data, resource data, work block data, specific project data and schedule results output data.

Within the global space demand database file, information is stored relating to the space demand values for generic resources. A data extraction algorithm is available for the extraction of global space demand for corresponding project resources, which are then stored in the resource data file (discussed below). The activity data file stores general information relating to activities on a particular floor, for example activity number, description, and association with other activities. This file also contains activity workspace data that defines activity space demand and workspace blocks for manpower, equipment and material. The resource database file stores available quantity for each resource type and the space demand requirement for the
individual resource. This is obtained from the global space demand database file. The activity workspace database file contains information defining the work areas allocated for each activity. As the construction progresses the available space varies due to work in place, and the space can be defined as it varies over time. The work blocks for material resources are defined separately, as material may be stored away from the work execution area. The project specific database file contains information defining the first and last floors of the project in addition to other project specific data such as future developments and implementations.

Within the SCaRC system, there are three groups of schemata structure, activity schemata structure, resource schemata structure and work-block schemata structure. The activity schemata structure defines such information as the resource code and quantity input by the user, the space demand of a particular activity and the results of the scheduling process. The resource schemata structure represents data such as the resource code, the resource type, the availability value and the space demand data for the particular resource. The work block schema stores information associated with the space work blocks. This includes such information as an identification number for the block and total workspace availability of the block.

The knowledge modules in the SCaRC system define the scheduling knowledge responsible for the reasoning process and the generation of the schedule. There are three knowledge modules, the external data module, the controller module and the sequence generation module. The external data module extracts the scheduling information from the database and is also responsible for sending generated results of the scheduling process to the database. The data is exchanged between the knowledge module and the database using ASCII files. The controller module controls the overall scheduling process by controlling the execution of the external data module and processing the scheduling cycles. The sequence generation module supplies the scheduling knowledge necessary to validate the various constraints and schedule each activity. The scheduling knowledge is stored in six processors: a vertical logic processor, a vertical knowledge processor, a resource scheduling processor, a space scheduling processor, a schedule processor and a resource modification processor.

4.5.4 Results
The system was tested on a hypothetical multi storey-building project (Thabet and Beliveau, 1997). The project was scheduled in the SCaRC system using horizontal and spatial constraints, with no vertical or resource constraints. The schedule generated from the system was compared to that of a basic schedule of work required for the construction and it was shown that the effect of limited workspace amended the project finish date. Additionally it was apparent that using the SCaRC system, several activities were split into two sections and a productivity loss was identified in the undertaking of some activities due to limited workspace availability.
4.6 Discussions and Summary

These five examples have demonstrated that space is a valuable resource on the construction site. Various research efforts are underway to establish how space can be planned during the pre-construction phase.

SightPlan utilises expert system knowledge to assist with site layout planning. Although the system uses processes and knowledge extracted from construction planners, it acts as a framework as the processes were only applicable to the construction of power stations. Due to the site layout being the initial process, the system was not tested where conflict occurred between the materials and the space required by an activity or a path. In addition to this the materials were constrained by the position and dimensions of ‘permanent’ and ‘temporary’ facilities with no account of the space required to install the permanent components.

MoveCapPlan is an extension of the basic MovePlan system that has the ability to schedule the layout of materials and temporary resources within the confines of the construction site. MovePlan allows the planner to stay at the centre of the decision making process by providing templates of resources and materials to be positioned on site. Using the CPM schedule and resource characteristics as input MovePlan provides ‘templates’ of each of the materials that exist for a defined time frame. The addition of the CAPSY module to MovePlan allows the dimensions and locations of materials to be measured in real time and so allows the ‘templates’ to be updated as the positions and size changes. This applies some dynamics to the layout process as the layout can be amended throughout time and as resource levels change. The location of the materials can also be measured however this has to be carried out manually.

Yang is currently investigating the issue of material routing within the site confines. This work relates to one of the specific construction spaces identified by Riley, i.e. paths. The work does not output information that could be used directly in a 4D model, however an extension of the work could be used for this purpose in the future. The results and validation of the work have not yet been carried out and so its potential usefulness cannot be concluded.

The work by Riley aimed to take the 4D work in the previous section one stage further, by applying actual physical workspaces as objects in the 4D analysis. This identified four types of space required to undertake work and postulates that these should be included into the simulation. Each of these spaces should have dimensional properties and temporal properties i.e. they should have a start and finish date for usage in much the same way as components within the constructed facility do. The work also proposes assigning a density to the construction space that describes the ability of that space to share with another workspace. The inclusion of these spaces in the 4D simulation provides a more robust rehearsal of the schedule, assisting in the identification of time-space conflicts.

The development of the SCaRC system by Thabet and Beliveau, presents the inclusion of spatial information as a constraint on the scheduling process. The system demonstrates that utilising space can highlight potential problems with the schedule and highlight possible congestion between activities. The system is
however only designed for the construction of multi storey constructions and the method of analysing space congestion using the space capacity factor is hypothetical and does not utilise real world information.

The group of work reviewed in this section has each concentrated on the aspect of space on the construction site. With the exception of Riley and Thabet and Beliveau, they have dealt with the scheduling of space for materials and temporary or permanent facilities. The work undertaken by Riley advances this one stage to discuss the space requirements to execute tasks in order to construct the permanent works. Materials on the construction site are dynamic and this is recognised by each system however the update of these positions and dimensions are really only dealt with by MovePlan and MoveCapPlan. The work does infer however, that space used by materials on the site is critical to the overall space needed on the construction site, and this could potentially have effects on the space required in order to execute the various tasks on the construction schedule.

The work undertaken by Thabet presents the Space Capacity Factor (SCF), which postulates that the congestion of a workspace can affect the productivity of the activity execution thus causing a variation in the duration. Whilst these productivities are hypothetical real world values and productivity-SCF curves could provide information that could be utilised by VIRCON.
5.0 SPACE TIME CONFLICTS ON CONSTRUCTION SITES

In order to fully analyse the construction schedule, the space requirements for the various activities have to be taken into account to identify potential spatial-temporal conflicts. This analysis of time-space conflicts on the construction site is an area of emerging research initiatives. This section of the report identifies research developments aiming to detect and evaluate these conflicts to provide a more reliable construction schedule. Work in this area has concentrated on two main regions, notably the conflicts caused between material locations on the construction site and the identification of time-space conflicts between execution space required for activities contained in the construction schedule.

5.1 Modelling the Space Behaviour of Construction Activities
5.1.1 Background
Completed in 1994, this work was undertaken as a PhD study by David Riley at Pennsylvania State University. The work identified that building construction requires space to move, store and fabricate materials, however no formal description existed of the reasons construction activities need space. The work also identified that the relationship between required space and the sequence planning process was not clearly defined. Because of this, planning efforts were short term, relying on the experience of construction planners to visualise and anticipate spatial problems that may arise.

5.1.2 Objectives
The overall aim of this research was to develop a space-planning model, which could be applied to multi-storey construction. The model defined the spatial requirements for various construction activities. The model would also prescribe a process for creating a construction sequence that took into consideration these spatial needs. To achieve this, the model would have to comprise a combination of a construction space model and a planning process model. Five objectives were defined to achieve this aim:

- Identify the space planning information needs and the current methods / techniques of space planning from the perspective of the construction manager.

- The definition of a construction space model that identified not only why space is needed on the construction site, but also typical patterns of how space is utilised throughout the duration of construction.

- The development of a planning process or sequence of decisions model. This would consider the space required when compiling the construction schedule. It would also identify the individual processes and information that influence planning decisions.

- To evaluate both the space and planning components of the Space Planning Model with regard to the accuracy of representing construction space.

- To apply the space-planning model to a real project to perform an evaluation.
5.1.3 Methodology

In order to achieve the objectives a space-planning model, which was applicable to multi-storey construction, was developed. The development of the model explored and analysed site issues that occurred on successful construction projects.

In the first stage, a study of space planning needs was undertaken by performing field investigations on ten construction sites. This identified the space requirements of different activities, the work patterns of activities and the techniques used to manage space. It was observed that on all of the sites, logistics plans had been developed illustrating the general use of space on the site. Another approach was to assign specific spaces on floors of buildings to different trades. From the studies it was identified that space was often wasted or used inefficiently.

The next stage undertook a pilot study on the sequencing of interior and perimeter finish trades of a multi-storey project. The study identified ways in which the space requirements affected construction sequences and the planning methods used to accommodate requirements.

Once the characteristics of planning methods were identified, they were used to form the basis for the space planning method. The characteristics were divided into 3 categories:

- Factors that affect planning – three factors were identified i.e. geographic location, building shape and type and the management style of the project.

- Planning requirements – i.e. a good project plan should provide spatial information, increase detail as required, consider the project needs and be easily communicated.

- Planning properties – space planning should be proactive, adaptive, simple to perform and graphically represented.

The fourth stage of this process was to identify the desired output of the planning process. This included a sequence in which trades moved through the project, the spaces occupied and the finished work installed by each trade.

Following this a construction space model was developed. This model used space types identified for each activity.

The penultimate stage was the development of a space-planning model. This is a detailed process model developed to describe a method for introducing space constraints into planning decisions. The structure of the model is described in the following section.

Finally a framework was formulated for planning guidelines. This identified that previously, rules had been developed for specific factors that affect the construction sequence. The work proposed that as spatial factors affecting sequences were identified, similar guidelines should be developed for decisions in the planning process.
5.1.4 Construction Space Planning Model
The Space Planning model is made up of two components. The Construction space model defines twelve spatial needs and the Planning Process Model that is used for developing a sequence of activities considering the spatial needs of activities.

Construction Space Model
The construction Space model describes the type of construction space needed by a task and the typical pattern in which these spaces occur and move over time.

The first stage of the development of the model decomposed construction work tasks into activity work elements. From this the relationships between construction work, work in place and available space could be defined.

The next stage of development was the definition of space required by each activity work element. These were split into two categories; areas, (spaces occupied by activity work elements) and paths, (spaces required for movement of materials and people etc). Within the construction space model twelve unique spaces are defined which are required in order to execute work elements in a multi storey building. The breakdown of the space relationship model along with the definition of the twelve space types required is shown in Figure 12
The final element of the construction space model defines Space Behaviour Patterns. For each space type, patterns were identified which describe how labour resources used the space over time. The modelling of the behaviour allowed relationships between activities to be developed. These patterns however represent the use of space based on selected methods of work, one of which may be more ideal than the other.

**The Planning Process Model**

The second part of the Space Planning Model defines a process to formally develop an activity sequence using the design and material information along with the construction schedule. The resulting plan describes the sequence of activities, the sequence that materials are bought in for use and the dynamic use of space during the project. This model was developed using the IDEF₀ modelling methodology and consisted of three levels of detail.

Level 0 provides an overview of the model. At this level the planning process is defined as Create Construction Sequence. It has input, describing information about the activities and materials needed), planning output, (consisting of a construction
plan representing a work sequence), a layout sequence and a delivery sequence. Planning controls provide information for decisions in the planning process.

Level 1 provides a more detailed stage of the model. The planning process, which was previously defined as Create Construction Sequence, is now divided into four procedures. The first of these is to identify the spaces required for each activity. In this function the schedule of activities, specified materials and design for the project are examined to determine what spaces are required for construction tasks. Subsequently the second procedure is initiated to generate a general layout for these spaces. In this process the locations for necessary spaces are assigned for each activity work element.

In the Sequence Activities procedure, the sequence of consecutive and concurrent activities is generated. A specific sequence to complete work is also defined. At this stage a sequence of material deliveries and a layout sequence are also developed. The final stage of the Level 1 model is the Resolve Conflicts process. At this stage the layout sequence is evaluated at selected time intervals to identify overlapping spaces for different activity work elements. Using the results, a decision is made to adjust the sequence, layout or method selection. This depends on the type of problem and the space behaviour patterns of the conflicting activities.

The Level 2 Planning Model provides even higher detail by further expanding each of the four processes described above. The Identify Required Space process is divided into four steps to identify material information, select construction methods, identify work activity spaces and identify material spaces and paths. The general layout process is divided into the following steps assign space behaviour patterns, layout room-level spaces, layout building-level spaces, layout floor-level spaces and create space layout. The Sequence Activities process is decomposed into the identify room sequence, identify building sequence, determine floor sequence and identify material delivery sequence processes. Finally the resolve conflicts process is divided into; identify interference and blockage, determine activities to be modified, determine conflict resolution method and determine conflict resolution action.

The relationship between each of the levels of the planning model is shown in Figure 13.
Figure 13: Planning Process Model
(Source: Riley, 1994)
5.1.5 Results

The model was validated using four case study projects. To test the models, four tests were carried out. The first two evaluated the models description of space by comparing defined space types and space behaviour patterns to those observed on site. The third test evaluated the accuracy of the Planning Process Model by comparing the content to current practices. The final test assessed the relationship between planning deficiencies and resulting interference problems.

The first test evaluated the definitions of space type as provided in the model. This was done to prove that any space found on the construction site was described by definitions in the model. In order to carry out the test, 74 activities were observed on the four sites, and examples of each type of space defined in the model were observed. There were no instances where a space occupied by an activity was not defined by one of the space types in the model. By proving that similar activities have similar spatial needs, the theory that the space needs of activities could be generalised was maintained.

The second test investigated the space behaviour patterns defined in the Construction Space Model. For each type of space the model defined between 3 and 6 typical usage patterns. These patterns were evaluated by observing construction activities and the work elements over time. The locations of work elements were mapped on floor plans to show patterns of movement. The test concluded that of the types of spaces observed, each could be described by a pattern in the model. In cases where comparable construction methods were selected and similar materials used, activities were seen to follow similar patterns. This supported the theory that the space use of particular activities can be generalised and predicted.

The third test evaluated the planning process model by performing interviews with experienced project managers. The goal of the interviews was to determine what space planning processes were deemed to be necessary by project managers. It was hypothesised that the project managers would consider most of the processes recommended in the model necessary. To support this, only one of the processes defined in the model was not referred to or considered important by the planners. The test also highlighted that several of the planners considered some planning processes to be more critical than others.

The final validation test investigated the relationship between the Planning Process Model and space-time conflicts on the construction sites. Specific processes were included in the model, which could overcome conflicts. The processes were developed by analysing conflicts on prior site observations, for example blocked paths, out of sequence work and double handling. From the results of the test it was shown that the failure to plan material paths caused a high number of conflicts. This was due to path planning decisions affecting all trades working in the buildings as each needed to move materials.

Following the validation, the models were used to develop plans and sequence activities on two construction projects. From the actual sequences used on site, various conflicts were identified. The sequence, which was developed by the model, was compared to that actually observed on site. Similarly the conflicts identified by the model were comparable to those observed during construction. This concluded
the usefulness of the model to identify and analyse space-time conflicts before they occur. On both the of the test case sites the model demonstrated the ability to create a pre-construction plan for a multi-story building and predict space-time conflicts.

5.2 MoveSchedule
5.2.1 Background
The MoveSchedule system was developed as a PhD study, completed by Zouein in 1996. The motivation for the work suggested that site layout planning helps to identify spatial conflicts within time periods. In order to solve the dynamic site layout problem, the system aims to minimize resource transportation and the costs associated with relocation of materials.

5.2.2 Objectives
The research had two main aims. The first of these was to develop a systematic approach that assisted planners in constructing dynamic site layouts for the project duration. This would take into account the constraints placed on the layout by the arrival and departure of resources on site. The second aim of the work further investigated the instance where no feasible solution can be found to the layout. In order to solve this problem, a systematic approach would be used to adjust the start dates of activities on the construction schedule so that a feasible solution could be obtained.

In order to achieve the aims described above the following objectives were established.

The development of a model that linked temporal and spatial data (assigned to resources) to the activities in a construction schedule. This model would characterise space needs of activities based on the methods and resources used to execute the task. In addition the interaction between resources and their locations should be represented.

Interactive computational mechanisms would be developed in order to assist the planner in establishing dynamic layouts.

The development of a heuristic construction algorithm that solved a constrained dynamic layout problem. This algorithm would search for solutions to any problem whilst minimising transportation and relocation costs.

Once the solutions had been found using the construction algorithm, a developed improvement algorithm would be used to solve the space-scheduling problem. This heuristic algorithm would seek solutions that minimised the project duration whilst being subjected to the space availability constraints.

The final objective was to test and validate the methods developed.

5.2.3 Methodology
The system is comprised of 3 modules that combine to form the underlying algorithm of MoveSchedule. The three modules are: The dynamic layout construction module, The Space Conflict resolver and the Scheduler. Each of these is discussed in more detail in the following sections.
**Dynamic Layout Construction Module.**

This module contains a model that characterises both the spatial requirements and the locations of materials on the site using a 2 dimensional representation. In addition an algorithm is utilised that satisfies the constraints on the acceptable positions of the material and minimises the cost associated with distances between interacting materials and their relocation.

The underlying model uses various methods to determine the locations of the materials.

The model only considers the layout of the site at discrete points in time that are marked by primary time frames. Primary Time Frames are defined as times between the appearance and disappearance of materials on the site. It is assumed that materials do not change position during this time period.

In order to represent the spatial characteristics of a material i.e. its position and location, a continuous 2D orthogonal grid is generated over the site. The materials are then modelled as rectangles positioned at either 0° or 90° in relation to the x-axis of the grid.

Each material on the site has preference measures and hard constraints. Preference measures consist of proximity and relocation weights. A proximity weight applies to a pair of materials and is used to quantify the amount of interaction between them. A high value means that there is a high amount of interaction between the two. A value of zero represents no interaction between the materials and their relative positions are insignificant. The relocation weight applies to a single material resource and provides a measure of the cost of relocating it. A zero value means that it can be easily relocated i.e. without cost. Hard constraints represent the 2 dimensional geometric relationships between the relative positions of two material resources.

The final section in the model is the undertaking of a dynamic layout function. This uses the Value Function of the Layout (VFL) to assess the quality of the dynamic layout. The VFL consists of two components: ‘P’ measures the cost associated with travel distances between interacting resources and ‘R’ measures the costs associated with relocating resources across layouts.

In addition to the model used, the module also uses an algorithm. This determines the positions of resources to satisfy constraints on their positions and minimise costs associated with travel distance and relocation.

The Primary Time Frame Layout Construction Algorithm (PTFLCA) is used to generate a layout of resources over a primary time frame. The PTFLCA uses a constraint satisfaction and propagation algorithm to determine sets of feasible positions for resources present within a time frame, subject to the hard constraints. Using these results PTFLCA positions the resources one at a time. Firstly the resource is positioned to meet the hard constraints with resources already in place within the layout. It then determines the position that minimises proximity costs associated with already positioned resources. Repeating the algorithm, each time starting with a different sequence of resources, can generate alternative layouts. The
maximum number of layouts produced can be set and once generated the Value Function of the Layout is used to determine the most valuable cost effective layout.

**Space Conflict Resolver**
The second module in the MoveSchedule system is the Space Conflict Resolver (SCR). When the dynamic layout construction module cannot find a solution that satisfies the space constraints of the resources, this module amends the schedule. The objective of the module is to reduce the total area requirement in the problematic time frame. This increases the amount of available space for the positioning of resources, whilst causing a minimum increase in project duration.

In order to achieve this the module adopts various strategies. Strategy A delays an activity that commences at the beginning of the time frame to start at the end of the problematic time frame. This delays the space requirements of the resource. Strategy B lowers the resource level of an activity within the problematic time frame and so lengthens the duration. Strategy C adopts the principle of off-site storage as a means to alleviate the space problem. This strategy does assume that off-site storage is available and removes a resource if it is redundant during the problematic time frame. The final strategy, strategy D, allows for user intervention in the program. This enables the user to manually amend the resource levels in order to solve the space problem.

For MoveSchedule to select one of the above strategies and solve the space conflict problem, the system can be operated in two modes. The first mode uses the Space Conflict Resolver in fully automated mode. In this mode the SCR expects the problematic timeframe as input and adopts either strategy A or B to solve the problem. The second mode provides the ability for user intervention. In this mode the user labels a resource in the layout that is to be removed. Taking this as input, the SCR selects a strategy that removes the resource whilst causing the minimum increase in project duration. The SCR does require user intervention, before applying any of the strategies that will result in the extension of the project duration.

**Scheduler**
The final module in MoveSchedule is the Scheduler. This module performs CPA calculations on the schedule as it is amended by the SCR. This uses forward and backward pass calculations to generate early start and finish dates of activities. Once the early start schedule is computed, the primary time frames are identified based on the schedule and the resources data. These are passed to the dynamic layout construction module as input for the PTFLCA algorithm. The scheduler is also responsible for the execution of the strategy selected by the SCR.

The integration of each of the three modules described above can be seen in Figure 14. These three modules form the space-scheduling algorithm that is the basis of the MoveSchedule system.
5.2.4 Results
To validate MoveSchedule, the system was used to provide a solution to space problems on construction projects previously undertaken. The former project engineer qualitatively assessed the solution.

The project modelled was a car park project constructed in 1986. The building was located in an urban area, and hence provided many permanent spatial constraints. The resource area requirements were derived from total quantities of material required and common practice in procuring and delivering them. Initially every activity was scheduled for their shortest duration. The scheduler firstly computed a schedule that corresponded to the shortest project duration and identified the corresponding primary time frames. This information was passed to the dynamic site layout module that generated a site layout for each of the time frames. The process found three space conflict errors and used strategy B in each case to solve the problem and construct the site layout.
MoveSchedule constructed a sequence of layouts for the site over the construction period. In doing this, the system actually amended the user-defined method of construction for one of the building walls to comply with the site space conditions.

5.3 Formalisation of time-space conflict analysis

5.3.1 Background

Completed in June 2000, this work was undertaken as a PhD study by Burcu Akinci at Stanford University. The work aimed to build on the work currently being undertaken at Stanford University and elsewhere investigating 4D CAD uses within the construction industry. The motivating case for this work was the observation of various time-space conflicts at 3 construction sites in the United States. One of these sites was observed in detail and it was found that the schedule could not be executed as planned due to three major time-space conflicts. In each case the contractor only realised the problem when it occurred on site, and with no time to explore options activities had to be delayed thus delaying the entire schedule.

5.3.2 Objectives

The ultimate aim of the research was to formalise time space conflict analysis as a classification task. In order to achieve this the research had three main goals:

- To detect conflicts in four dimensions
- To categorise the conflict according to taxonomy of time-space conflicts developed
- To prioritise the multiple types of conflicts between the same pair of conflicting activities

These aims were achieved by identifying three characteristics that make it difficult for project managers to identify, analyse and manage spatial conflicts. These characteristics were:

- The temporal aspects of time-space conflicts - Activity space requirements change over time and so time-space conflicts only occur for certain periods of time.
- Multiple types of time-space conflicts - Depending on the type of conflicting spaces, time-space conflicts can have many types, for example severe congestion, mild congestion and safety hazard.
- Multiple conflicts between a pair of conflicting activities - Multiple types of space required by an activity conflict with multiple types of spaces required by another activity. This results in multiple types of conflicts existing between the same pair of conflicting activities.

5.3.3 Methodology

The aims of the research were met by the development of two prototype systems. The 4D Workplanner Time-Space Conflict Analyser (4D TSConAn) automates the time-space conflict analysis process. The 4D TSConAn is linked to another prototype
system the 4D Workplanner Space Generator that automates the generation of workspace requirements of activities.

The 4D Work Planner Space Generator uses a project specific IFC based 4D production model as input. The user is then required to input the types of space needed for construction methods to be used using ‘Space Templates’. These templates relate to Labour crew space; Equipment Space; Hazard space and protected space. This space is described qualitatively i.e. relative to a reference object and quantitatively i.e. using volumetric parameters, length, width and height. The output of the space generator was a space-loaded production model representing the various types of space requirements of activities. These space types are intelligent objects, knowing when and where they exist as well as how much volume they occupy.

The project specific spaces used in the 4D SpaceGen were formalised as extensions of the standard production model, represented in IFC Release 2 Beta 4. In this standard, work methods are represented as a string within the IfcWorkMethod attribute of the IfcWorkTask class. This built on a representation already formalised (Aalami, 1998) and extended the construction method to include space requirement knowledge.

The 4D TSConAn prototype simulates the construction process according to the schedule developed by the project planner. It also includes mechanisms to automate the steps of formalising time-space conflict analysis. The four steps used in the formalisation were:

Detection of spatial conflicts in a given space loaded production model using the output from the 4D SpaceGen.

The system uses a combination of basic 3D geometric clash detection algorithms and discrete event simulation mechanisms to identify clashes within three-dimensional space and across time. These spaces are represented as rectangular prisms parallel to orthogonal planes. The detection of conflicts creates a list of conflicts between spaces required by activities and work in place.

Aggregation of the conflicts detected.

During this stage the system selects a pair of activities that conflict with each other and aggregates the conflicts detected. This is achieved using the total volume of each space required by a conflicting activity, adding the volume of the time-space conflict detected between the same pair of interfering spaces and calculating the conflict ratio. This conflict ratio is used to determine the level of congestion.

Categorisation of the conflicts detected.

The time-space conflicts detected were categorised according to the type of space conflicting and the conflict ratio calculated. Taxonomy was developed to categorise the conflicts between the various spaces associated with the activities and this is seen in Figure 15. This highlights five major types of conflicts.

- A design conflict occurs when a building component conflicts with another building component.
A safety hazard constitutes a conflict between a hazard space generated by an activity conflicts with the labour space required by another activity.

A damage conflict occurs when a protected space required by an activity conflicts with labour space, equipment space or hazard space required by another activity.

Congestion occurs when labour or equipment space for one activity, conflicts with labour or equipment space for another activity. There are 3 types of congestion; Mild whereby only a small portion of labour space conflicts with another space creating minimal productivity loss. Medium congestion that occurs when a sizeable portion of a labour crew space conflicts with another space significantly reducing productivity. Severe congestion occurs when a significant portion of labour space conflicts with another space causing a constructability problem.

The conflict could produce no impact on the construction schedule and present no productivity reducing problems.

Prioritisation of the conflicts detected.
In some conflict situations multiple types of spaces required by an activity conflict with multiple types of spaces required by another activity. This results in multiple types of conflicts between the same pair of activities and this needs to be prioritised. In prioritising and ranking these conflicts, the different problems each conflict can create were analysed.

The overall outline of the systems can be seen in Figure 16.
5.3.4 Results
In order to test the success of the time-space taxonomy, the conflict analysis formalism and the overall effectiveness of the 4D TSConAn system a validation was undertaken. This compared the retrospective time space conflicts observed at three construction sites with the results provided by the system. The time-space conflict analysis mechanisms implemented in 4D TSConAn successfully identified and categorised all of the conflicts observed in these three cases.

In addition the developed taxonomy was tested against actual manual observations taken at a further site using the same taxonomy. The results of this showed that the conflicts categorised using the time-space conflict taxonomy were the same as those observed at the construction site.
5.4 Discussions and Summary
Section 3 of this report reviews the current tools available to assist project scheduling. Following this, the reviewed work identifies that scheduling and use of space of the construction site is critical to the completion of a project as demonstrated in the previous section. The logical progression to this is the analysis of the spaces used by construction activities to identify time-space conflicts that will affect productivity and task execution.

The work by Riley developed the space-planning model, comprising a construction space model and a planning process model. The construction space model identified the space required in order to carry out activities and how these spaces moved over time. The planning process model was defined to formally develop a sequence for the activities using the IDEF0 modelling methodology. During the planning process the spaces generated are called for each of the tasks and are modelled accordingly. Following this, conflicts between the spaces for activities can be determined. The model was developed for, and was tested on, schedules for the construction of multi-storey buildings. The applicability of this model to other construction projects would require further investigation. This work concludes however, that spatial requirements of activities can be modelled and conflicts can be predicted on site.

MoveSchedule is a system designed to solve space-time conflicts between materials stored on the construction site. This system provides dynamic layouts of the site over time, taking into account the arrival and departure of resources as well as geometric constraints. To generate the layout the system uses a Dynamic Layout Construction Module that considers the layout of the site during calculated time frames. If the module can determine no suitable layout, the system utilises another module, the Space Conflict Resolver. This module makes amendments to the construction schedule in order to reduce the amount of space required on the site during the problematic time frame and hence increases the amount of space for the materials required. This amending of the schedule does in fact use some form of artificial intelligence and applies strategies to delay particular activities, lower the resource level etc.

The MoveSchedule system does however assume that the material resources remain at a constant location and retain constant dimensions throughout the period in which they are present on site. It could be viewed that this is not a true representation of real life situations. In reality the material would diminish as work progressed. This reduced space could provide areas in which further work could be undertaken, or could be utilised for other construction purposes.

Work recently complete by Akinci is the most recent research to investigate the area of space-time conflicts. This work formalised time-space conflict analysis in 4D and provided a system that detected and categorised these conflicts. These conflicting areas were then displayed via a virtual reality interface.

The work produced two prototype systems. The 4D SpaceGen uses templates, allowing the user to specify the amount and type of space used to execute a task. The modelling of this space, as a 4D object, was an area postulated by Riley as discussed previously. The information from this system is used as the input for the 4D TSConAn prototype.
This module simulates the construction process using a supplied schedule. During the simulation stage conflicts are detected between the space required to carry out a task, work already ‘in place’ and activities conflicting with each other. A conflict ratio is calculated between activities that conflict with each other and using this ratio the conflict can be categorised. In addition to the conflict detection, the system also utilised the emerging IFC standards to represent work methods within the IfcWorkMethod attribute of the IfcWorkTask class. This work demonstrated the use of generic descriptions of workspaces required for construction activities and provided a simulation in 4D that had the ability to detect conflicts. Again the spaces generated remained constant in both dimension and location for the entire duration of the construction task. This does not support the dynamic nature required to undertake the construction task.

The work in this section has demonstrated that the time space conflict of activities is vitally important to the construction process. Existing technologies in the form of 4D can be utilised to solve these problems (demonstrated by Akinci) and the use of artificial intelligence can be used to solve some forms of conflict (Demonstrated by Zouein). Using modelling techniques, the construction process can be rehearsed before site operations begin and potential space-time conflicts can be highlighted prior to their existence. None of the work however fully represents the dynamics of the construction process in its entirety. Although resources and space are modelled and represented for various time frames it is often the case that space use varies within the time frame, and spaces can be occupied for the execution of more than one task.
6.0 INDUSTRIAL RESEARCH

6.1 Overview
The previous section has demonstrated that various research institutions have identified that the area of construction planning can be greatly improved by using visualisation techniques. In addition, the modelling of the processes involved in the construction of a facility can be beneficial. Although many of these research areas have involvement from industrial partners and collaborators, many construction companies throughout the UK are seeing the potential in this area and have embarked on their own research. The following sections discuss some of these projects in more detail, in particular relating to the work being undertaken by the collaborators of the Virtual Construction Site.

6.2 WS Atkins Consultants
6.2.1 Background
WS Atkins was founded in 1938 and is now one of the UK’s leading consultancies utilising new technology as an integral part of its operations. Since 1996 WS Atkins have been using, promoting and developing virtual reality tools and techniques as a valuable design tool.

6.2.2 Examples
WS Atkins have utilised virtual reality technology to assist with design reviews, assessment of space usage, visibility issues and construction sequencing. The following examples were reported by Kerr (2000).

One area of use for virtual reality is an extension to a school building. Produced in association with the Laing Technology Group (as part of a ‘Partners in Technology’ Group) the aim of the work was to show the same 3D CAD model in a virtual environment with different presentations. This enabled each of the various disciplines working on the project to see different views of the same model, for example structural, Mechanical and Electrical etc. This provided an instant visual overview of the design inputs.

Another project where virtual reality was used to assist visualisation was the Docklands Light Railway, Lewisham Extension. A model was created to show the interior of a typical voided bridge deck. This was used to visualise internal accessibility for maintenance purposes. In addition to the basic model, interaction was also added to enable the user to display various features of the bridge for example tie down stiffeners and maintenance operatives.

Whilst not directly related to construction planning and 4D simulations etc., these examples show that WS Atkins are utilising virtual reality technology to assist in the design process.
6.3 Stent Foundations
6.3.1 Background
Stent Foundations were founded in 1936, and are currently one of the UK’s larger piling and ground engineering contractors. Believing that virtual reality (VR) software can assist in project planning and visualisation Stent Foundations believe the potential benefits of producing detailed interactive VR models are numerous. Stent believe they could provide a useful planning tool on sites where there are spatial restrictions and aid communication with the client or main contractor.

6.3.2 Examples
The following examples of how Stent foundations are utilising virtual reality technology are reported on the Corporate Website.

Virtual City Site - A city centre model was developed to show a CFA rig working in restricted space. The environment also includes for a pile boring sequence and concrete wagon delivery.

Virtual Railway Site - A railway model was developed to show a C30 rig and crane working in close proximity to a railway track. This environment includes for a pile boring sequence and reinforcement cage placement.

Virtual River Site - A river model was developed to show sheet piling installation using a frame close to a river. This environment includes for frame installation sequence and pile installation.

Although not directly related to the planning process and space scheduling the VR models were utilised to visualise how the piling plant would operate in congested areas. For example at the railway site the model was used to depict how close the plant would be to the live railway line and so identify any spatial conflicts which could arise.
6.4 Discussions and Summary
The reviews undertaken in this section provide evidence that not only is academia investing heavily in the area of project planning and visualisation techniques but Industry is also investigating potential benefits. They to realise that using these techniques provides a greater understanding of the project planning process and the identification of spatial interferences on the construction site.

The use of visualisation techniques by companies such as WS Atkins and Stent Foundations prove that this technology is not committed to academic research but has practical applications within industry. The use of virtual reality by Stent to visualise the location(s) of a piling rig and it proximity to the railway line prove that visualisation can be used to assist the planning process. Normally these safety issues would have to be addressed on site, as they could not be viewed before work commenced.
7.0 OVERALL CONCLUSIONS

This report has demonstrated that the potential for supporting the decisions of construction planners is great and present technology can be utilised to achieve this aim.

The report has shown that during all stages of the construction planning process, visualisation techniques can assist the construction planner in providing a more robust project schedule. Ranging from using 3 dimensional models to convey the complexities of the construction, to using 4D CAD to analyse the schedule and highlight logic errors, visualisation can assist the planning process.

4D CAD is an area that mobilises a large amount of research effort. The technology is constantly being extended and updated to become more functional. Originally a tool to visualise the objects, as time elapsed work has been carried out to include ‘annotations’ to describe components as they are viewed on screen. In addition 4D is being used as a tool to assist not only with the schedule analysis but also other factors during construction such as cost. One inherent problem with 4D relates to the generation of the schedule. In order for a 4D simulation to be created a schedule must first be generated by the construction planner. Some of the research reviewed cites this as this beneficial, as it retains the planner at the centre of the scheduling process, others utilise expert systems to first create the schedule and generate the 4D simulation. It is proposed that the role of the VIRCON is that of a decision support system and as such, retains the planner as the central focus of the planning tasks.

A further problem exists with 4D technologies as only building components are modelled and linked to the construction schedule. No account is taken of the space required to execute the task or tasks needed to build the component. This is identified in work by Riley (1998) that concludes space utilised for the construction of components should be included in a 4D simulation. The work by Akinci (2000), builds on this proposal and models space requirements explicitly as an object.

As has been demonstrated, some of the previous work in the area of construction schedule analysis has utilised the 4D CAD concept to present rather than analyse the results of schedule analysis. Using this 3D visualisation concept, all parties can relate to objects, as they will exist on the construction site. It can be concluded however that the use of 4D CAD is one the most powerful tools and should be utilised for the presentation of visualisation results for the VIRCON system.

Space required to execute construction tasks is an area that is only recently becoming accepted as an area where further research is required. The space used by materials on the construction site however, is an area that has been the subject of previous research efforts. The scheduling of space usage within the bounds of the construction site is an area that has produced both expert and decision support systems. SightPlan is an expert system that uses inherent knowledge of materials and constraints on their positions to determine storage locations on site.

In addition to the expert system, MovePlan is a support system developed to retain the planner at the centre of the layout control. Whilst using some analysis skills to depict the materials that would be present on site during a time frame, the planner
retains overall control. Using the schedule information, the system is able to deduce the materials present on site during a particular time frame and provide ‘templates’. These depict the dimensions of the materials, along with a site layout, as it exists. The planner is then able to position the templates on the site layout. Using a real time positioning system, the size and location of the material areas can be updated to reflect the real situation on site.

The concept of utilising ‘templates’ could provide a basis for presenting spatial objects in the VIRCON system. In addition to modelling execution spaces for each of the components, space has to be scheduled for other objects such as temporary and permanent works, including plant objects. Each of these could be specified uniquely as each is different, however in many cases (for example plant) the underlying attributes for the space are the same. For example, a crane has spatial attributes for both its base size and rotation, however these values would vary depending on the size and model of the plant.

In a further development in the area of materials planning, a system that uses both principles of decision support and expert knowledge was developed. MoveSchedule divides the construction schedule into time frames depending on activities, and generates a material layout for the site. The systems progressed this further by providing the ability to detect spatial conflicts. Once detected the schedule was amended to provide more overall space within the site boundaries and accommodate the materials.

The most recent work has investigated methods of identifying and formalising time-space conflicts on the construction site. Some original work in this area (Riley, 1994) identified that space was required for the undertaking of construction activities. Subsequently a model was developed that provided a method to relate the activities needed in the construction schedule to their space requirements. Using these temporal and spatial relationships, space-time conflicts could be detected prior to construction beginning and could be resolved.

More recently work at Stanford has used the spaces required by construction activities to further the 4D simulation and analyse time-space conflicts. Spaces are generated using generic descriptions, and these spaces are identified as objects to be included in a 4D simulation. From the simulation conflicts can be identified between space used for activities and between activity space and ‘work in place’. Once highlighted the conflict can be categorised using a defined taxonomy. This categorises the conflict in terms of its importance and its potential effect on other construction operations. A major disadvantage of this system however, is its inability to model the spaces as dynamic objects. In the simulation the space remains both constant in dimension and location throughout the duration of the task. Due to this no account is taken of the spatial variations during the life cycle of the activity period.
REFERENCES


16. Coles, B. C. and Reinschmidt, K. F. (1994) Computer-Integrated Construction: Moving beyond standard computer-aided design to work in three and even four dimensions helps a project team plan construction, resolve conflicts and work more efficiently. Journal of Civil Engineering, ASCE. Volume 64, No. 6


