Technical Evaluation:
VIRCON Task 12 Report

**Steve North, Graham M Winch, Nash Dawood,
Dave Heesom, John Kelsey, Eknarin Sriprasert and Zaki Mallasi**

Manchester Centre for Civil and Construction Engineering
UMIST

2003

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

Manchester Centre for Civil and Construction Engineering
UMIST
PO Box 88 Sackville Street
Manchester M60 1QD
United Kingdom

CONTENTS

FIGURES

TABLES

1: Introduction

The purpose of this research report is to provide an overview of the development of the VIRCON system (VCS), and to provide a technical evaluation of the delivered VCS software as the task 12 deliverable. The VCS consists of various software components developed by the research teams at UMIST, University College London, University of Teesside and University of Wolverhampton in collaboration with a number of industry partners. This report will first summarise the original objectives of the VIRCON project, and then describe the delivery of the research against those objectives. The report will then go on to evaluate the delivered prototype system in a number of ways :

- against an “idealised” development utilising information modelling techniques;
- against the “as recommended” criteria which are the outputs from task 3;
- against the current state of the art in information environments for construction project planning;

Finally, this report will review the limitations of the system as delivered arising from the above evaluations, together with our own user evaluation in task 10. It will then make recommendations for future work.

2: The VIRCON Vision

The VIRCON Vision is rooted in two principal observations :

- There is increasing pressure on the construction planning process : clients are demanding much improved performance in the construction process; the generation of construction planners with detailed site experience is retiring; and new techniques are being developed for the construction planning process.
- New software tools – particularly those associated with virtual reality (VR) - are providing new opportunities to develop and enhance the tools available to construction planners, thereby giving much more intelligence to the process.

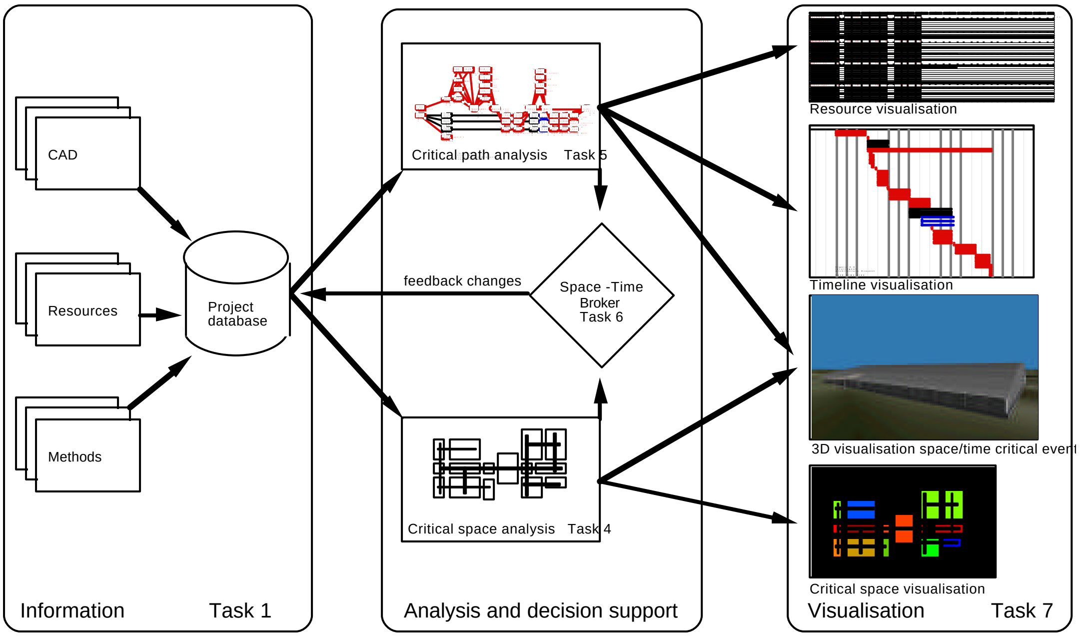

Figure 1 The VIRCON Vision

source Kelsey et al (2000)

The aim of the VIRCON project was to develop a decision-support tool for strategic construction project planning. In particular, we decided to focus on the planning of the allocation of tasks in the work breakdown structure to task execution spaces on site. This is an area which had received very little attention at the time of our proposal, and we believe that our work here remains at the leading edge. Our proposed research involved both the development of a planning tool which we dubbed critical space analysis (CSA), its combination with critical path analysis (CPA) in a space-time broker, and the development of advanced visualisation tools for both CPA and CSA. Figure 1 presents the original VIRCON vision for construction project planning, and its principal components.

The VCS comprises three main elements:

- a project database which integrates relevant geometric, method, resource and task information;
- the analysis of time critical and space critical tasks, and the brokering of these two aspects in project planning;
- the visualisation of the project process with respect to time and space.

The VCS was planned to be delivered through 12 tasks, shared between the three collaborating universities. The move of the Principal Investigator from UCL to UMIST during the project meant that UCL's responsibilities were shared with UMIST. The unfortunate incapacitation of the designated project manager from Carillion also meant significant changes to task 1, and this task became, in effect, a UMIST responsibility.

Task 1 Project Management

Task Manager : Carillion/UMIST

This task covered overall project management of the research and co-ordination of the team, and responsibility for chairing the Steering Committee.

Task 2 : Data Capture and Data Base Development

Task Manager : Teesside.

Research Resource : Teesside

Collaboration AMEC; Bond Bryan; Services Design Associates; ABB

The principal activity here was the development of the VIRCON database which is at the heart of the VIRCON system. This was developed in MS Access following a literature review which suggested that object-orientated data bases were less suited to this task than relational databases, and that the excellent interconnectivity and widespread diffusion of MS Access offered considerable advantages. The use of industry foundation classes (IFCs) was also rejected due to their limited level of development in 2000, and lack of diffusion in industry. AutoCAD was selected as the CAD software due to its widespread diffusion, and good database interconnectivity. The interface using OLE DB was written as a macro in AutoCAD called DataExtractMan. An important decision was made to fully adopt industry information standards, and so the VIRCON data base is fully compliant with the BS 1192-5 standard for information layers in CAD, and the Uniclass project information classification standard.

In order to populate the database so that it could be used as a development tool, project data was obtained for AMEC's Centuria

Building at the University of Teesside and input as 2D drawings and a construction programme in MS Project.

Deliverables:: a structured relational data base and 2D (x & y) model of the Centuria Building project for use in tasks 5, 6 & 7.

See: Dawood, Sriprasert, and Mallasi (2003a)

Task 3 : Technology Opportunities and Potential

Task Manager : Wolverhampton.

Research Resource : Wolverhampton

The aim of this task was to review the state of the art at project commencement, both in construction and more broadly. Three reports were produced. The first reviewed current research, and identified three relevant bodies of work :

- 4D planning research focused on developing techniques for visualising the construction of the 3D product model through time;
- research focused on various aspects of planning the use of space on construction sites, focusing on both site layout and task execution;
- research on clash detection between differing spatial requirements.

The second report reviewed 12 critical path analysis (CPA) software packages, and recommended the adoption of MS Project due to its excellent functionality, widespread diffusion, and excellent interconnectivity.

The third report cast its net more widely, and identified the use of drag-and-drop templates for construction plant, the use of IFCs, and web applications for project information management.

Deliverables: three reports on the potential applications of manufacturing process visualisation techniques; choice of MS Project for the VCS; evaluation protocol for task 12.

See: Heesom and Mahdjoubi (2002 a, b, c)

Task 4 Understanding Planning Decisions : Requirements Capture

Task Manager : UCL.

Research Resource : UCL

Collaboration : Skanska; Carillion; Balfour Beatty; AMEC

This task constituted the main requirements capture phase of work. Detailed interviews were conducted with a sample of 18 experienced planners across the four principal collaborators to identify current practice, and to elicit their requirements for the VCS, supported by process maps. The most striking findings were how little time there was for the effective planning of the job (because of very short tender periods) and the level of missing or incomplete information available at pre-tender stage. Post-contract planning was then constrained by the broad-brush approach required for pre-tender planning, and the necessity to leave much detailed planning to trade contractors. An important conclusion from this research was that the VCS needed to fit within current planning practice to have any hope of being implemented, and needed to allow broad-brush analysis. From this we developed our specification of the VIRCON system as a “quick and dirty” (QUAD) system, which would allow frequent amendment and would not require major changes in current planning practice, thereby allowing allow speedy implementation. Critically, the tool has to be easy to use requiring little additional training. In addition it should interface easily with other software in current use by the contractor. The planners interviewed reported that they would strongly welcome such a system.

Deliverables : report on the state of the art in construction planning ; evaluation protocol for task 10.

See: Kelsey, Winch and Penn (2001).

Task 5 Prototype Critical Space Analysis System Development

Task Manager : UMIST

Research Resource : UMIST

Our early work identified the requirement for a mark-up tool that would allow the definition of the spaces available on site. The CAD files in the database only provide the building as intended by the designers. For much of the project life-cycle, many of the components in the building do not exist. Therefore, the CAD drawings alone cannot be used to define available space, and they require further manipulation. A simple-to-use mark-up tool called AreaMan was developed which takes the weekly 2D AutoCAD drawings produced by PlantMan and allows the planner to mark them up for space availability week by week, producing 2D drawings in .dxf format. If necessary, AreaMan can work independently of the database, taking .dxf format inputs directly from the designers’ CAD files. The rationale for this tool is based on the conclusion that spatial planning on construction sites is essentially a 2D problem. Any work at height would “sterilise” the area below it for both practical reasons of providing access, and safety reasons.

Conceptual work building on the recent literature on construction space planning was also undertaken to develop a terminology for construction space use, and “critical space” was defined as any space with a loading of 100 where this is calculated as a ratio of required space to available space.

Deliverable: space mark-up tool : AreaMan

See: North and Winch (2002)

Task 6 : Visualisation Development: Whole Building Visualisation

Task Manager : Teesside.

Research Resource : Teesside

Collaboration : AMEC

Using the output from task 2, a VR model for rehearsing construction schedules of the Centuria Building was developed and provided a platform for visualising the temporal distribution of tasks for the structural works. This task sought to develop a methodology for integrating standard scheduling software with the 2D model for visualisation purposes. First, this model was manipulated to produce a 3D effect – sometimes known as 2½D, to distinguish it from true 3D product models. This first step in this manipulation is to ensure that all objects are drawn as polylines. Then the *change property* feature in AutoCAD can be used to allow the input of *elevation* and *thickness* values to give the third dimension. The *grouping* of these objects then allows their linkage with the MS Project programme. After populating the database with DataExtractMan, the 4D effect (3½D) simulation can then be run either in AutoCAD itself, or using a VR interface such as DDDoolz. This tool was dubbed ProVis.

Deliverables: 3½D space and time visualisations in an AutoCAD environment.

See: Dawood, Sriprasert, and Mallasi (2003b).

Task 7: Visualisation Development: Specialist Trades Visualisation

Task Manager: Wolverhampton.

Research Resource: Wolverhampton.

Collaboration : Balfour Beatty; ABB

This task was executed in close collaboration with task 6. Two specialist trades were selected which are particularly challenging for planners – groundworks, and mechanical and electrical services. Data for the former visualisation came from Balfour Beatty's University College Hospital site, while Centuria Building data from ABB were used for the latter. A number of tools were developed :

- ResourceMan is a database tool to allow the development of a library of the spatial requirements of human and plant resources;
- PlantMan is used to develop weekly spatial layouts of the project. These layouts can be populated using drag and drop templates of plant and temporary structures from ResourceMan. Plant movement paths can also be assigned. There is also the facility to specify datum levels for the various floors of the building.
- ClashMan allows the identification of clashes between the temporary objects positioned in PlantMan and the permanent objects of the building completed to date derived from the database.
- SpaceVis provides a VRML visualisation of the progress of the building week by week. This is a platform independent tool which can be run using any standard VRML player.

Deliverables : 2½D visualisations of spatial assignment of temporary works and 3½D space and time visualisations in a VRML environment.

See: Heesom and Mahdjoubi (2002d)

Task 8 Prototype Space/Time Broker

Task Manager UMIST.
Research Resource : UMIST

This task takes the data provided by AreaMan and PlantMan on spatial allocations, and then analyses them in relation to the programme to identify areas of spatial overload. This is visualised through a traffic-light interface which simultaneously shows the loading on the space, and the status of the tasks allocated to that space for that week in relation to the critical path. This space/time brokering system was developed as a client/server application dubbed SpaceMan. The system can be used either in terms of decision support to identify spatial overloads, or it can be asked to attempt to resolve these overloads by using a "brute force" rescheduling algorithm. The results of this analysis are then used to update the database for use in the visualisations developed in tasks 6 and 7, and also to update the MS Project file.

Deliverable: prototype Space/Time Broker software : SpaceMan.
See: North and Winch (2002)

Task 9 System Integration

Task Manager : UMIST.
Research Resource : UMIST; Teesside; Wolverhampton.

This brought together existing CPA software together with the results of tasks 2, 5, 6, 7 & 8 and tested the prototype of the whole decision support system in the form of the *Virtual Construction System*. This identified a number of software glitches which were resolved collaboratively by the whole VIRCON team. In addition, systems architecture and IDEF0 maps were drawn, and a VCS toolbar was developed to allow easy movement between the various VIRCON tools.

Deliverable : prototype VIRCON System v. 1.3.
See: North and Winch (2003).

Task 10 User Evaluation and Testing

Task Manager : Teeside
Research Resource : Teesside; UMIST
Collaboration Balfour Beatty; Skanska; AMEC.

A live project being constructed by Skanska – the Westmoreland School in Stockport - was chosen to provide the data for evaluation sessions. This was chosen because of its use of the CLASP prefabricated system, which made the investment in database set up potentially more attractive. Groups of experienced planners were invited to evaluation sessions mounted on computer clusters at Teesside and UMIST. The testing of system on live projects supplied by the industry collaborators against the protocol developed in task 4 produced valuable results, and gave confidence in the viability of the QUAD

approach and the value of the tools developed. Both strengths and weaknesses of the system were identified, and suggestions for further improvements made.
Deliverable: report on VCS in use and recommendations for further development.
See: Dawood, Sriprasert, and Mallasi (2003c).

Task 11 Dissemination

Task Manager : Teesside.
Research Resource : Teesside; UMIST; Wolverhampton.
This task is current at the time of the preparation of this report.

Task 12 Technical Evaluation and Review

Task Manager : UMIST
Research Resource : UMIST, Teesside, Wolverhampton, UCL

This task provides an overview and evaluation of the achievements of the VIRCON project. In addition to summarising the task outputs and describing the development process, it evaluates the output of task 9 against two benchmarks:

- The system as proposed in the grant application;
- Research in the area over the last two years.

It concludes that the objectives of the proposal have been substantially achieved, and where objectives have not been fully achieved, there are very good reasons for this. It also includes that, compared to other current research, the VIRCON system represents both a significant contribution to our knowledge in the area of VR applied to construction planning, and a distinctive approach which is led by the requirements of construction firms, rather than technical possibility. Limitations of the system as delivered are also identified, and avenues for further work indicated.
Deliverables: overview of VIRCON project achievements, and report on potential for further development of the VCS.
See: North, Winch, Dawood, Heesom, Kelsey, Sriprasert, and Mallasi (2003).

3: System development

The chosen development approach for the VIRCON System utilised existing third-party applications, such as AutoCAD, Microsoft Project, and Microsoft Access. The advantage of this method is that maximum effort can be applied to research-related software development. The alternative is to develop the entire system from the ground up, without any reliance on existing software. A stand-alone development route would necessitate the duplication of existing functionality, such as CAD editing and data handling. This might best be described as 'reinventing the wheel'. However, it does offer the advantage that all bugs are addressable by the research developers. Section 4 will describe an idealised, hypothetical approach to developing the VIRCON System from scratch.

1. VIRCON tool bar (launch buttons for all components)
2. AutoCAD
3. Microsoft Access
4. PBS exporter macro (AutoCAD to Microsoft Access)
5. ResourceMan (stand-alone database management tool for legacy collection of resource data including Required Space)
6. Resource Standards Database (Microsoft Access format for use with Resource Man)
7. Microsoft Project
8. Microsoft Project interface (a set of VBA macros, views, mappings and toolbars for importing, exporting data)
9. VIRCON Database (Microsoft Access format)
10. PlantMan (a stand-alone 2D tool for adding temporary/plant template objects)
11. ClashMan (a stand-alone tool for detecting clashes with temporary/ plant
12. AreaMan (a mark-up tool for identifying Available Spaces)
13. SpaceMan Client (stand-alone CSA tool)
14. SpaceMan Server (stand-alone CSA tool)
15. SpaceVis (VRML 4D Project Visualiser)
16. ProVis (AutoCad 4D Product Visualiser)

Table 1 VIRCON System Tools
source : North and Winch (2003).

The implication of including third-party components was that the software development sequence could not be optimised. The third-party software was already in existence and the new development had to fit in around it. This required a reactive development approach, where much of the research team's focus had to be on component interoperability. Figure 2 provides an overview of the VIRCON tools, which are listed in table 1.

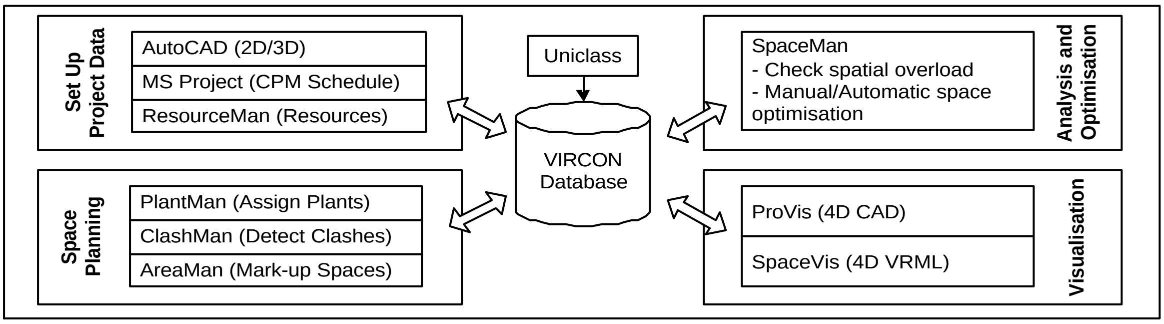

Figure 2 Overview of the VIRCON Tools
source : Dawood et al 2003c

Several of the tools were developed both concurrently and incrementally. However, it is possible to approximate the development sequence as follows:

- VIRCON Database (vircon.mdb)
- DataExtractMan (PBS exporter macro- AutoCAD to MS Access)
- SpaceMan Client
- SpaceMan Server
- PlantMan
- AreaMan
- Microsoft Project Interface
- ProVis (AutoCad 3½D Product Visualiser)
- SpaceVis (VRML 3½D Project Visualiser)
- Resource Standards Database (ResourceStandards.mdb)
- ResourceMan
- ClashMan
- VIRCON tool bar

VIRCON System release			
	Release date	VIRCON task	purpose
v1.0	Aug 2002	Task 9	Testing-UMIST development team
v1.1	Aug 2002	Task 9	Testing- broader development team
v1.2	Sept 2002	Task 10	User evaluation
v1.3	Feb 2003	Task 11/Task 12	Post-evaluation dissemination

Table 2 VIRCON System Version History
source : North and Winch (2003)

These different tools were integrated during the course of 2002 through a number of versions, as detailed in table 2. Version 1.3 was released in February 2003 for dissemination throughout the collaborating companies on the VIRCON project. The release CD also contained all 10 VIRCON research reports.

The VIRCON system utilised a range of programming languages, protocols and standards. These included :

- ActiveX controls (for DXF functionality and implementation of the SpaceMan Client/Server architecture)
- C++ (programming language for SpaceMan, AreaMan and VIRCON Tool Bar)
- CAD layering standards ISO DIS 13567 (ISO 1998a, 1998b, 1998c) and BS 1192-5:1998 (British Standards Institute 1998)
- DXF (AutoDesk 2000)
- HTML (used for help pages)
- Microsoft Data Access Objects (DAO) v3.6 (Microsoft 2001)
- Microsoft Jet v4.0 (underlies Microsoft Access database technology)
- Microsoft ODBC (used by components for data exchange)
- Structured Query Language (SQL)- used by SpaceMan for requests to the VIRCON database and internally to the database for content processing.
- Microsoft Foundation Classes (MFC) - used with C++ in the construction of SpaceMan, AreaMan and the VIRCON Tool Bar.
- UNICLASS (Crawford et al 1997) - used as information model on the database.
- User Datagram Protocol (UDP) from TCP/IP (used as a message transport for SpaceMan Client / Server).
- Virtual Reality Modelling Language (VRML) - used by SpaceVis for the 3½D visualisation.
- Visual Basic (programming language of choice for all University of Wolverhampton components).
- Visual Basic for Applications (VBA) macros (used for DataExtractMan, Microsoft Project Interface and ProVis).

4: An ‘idealised’ development sequence for the System utilising information modelling techniques

In Section 3, it was noted that the VIRCON System was developed using a reliance on third-party software. This is one of two possible approaches that could have been adopted for developing VIRCON. The chosen methodology can be summarised as, ‘use third-party solutions and fill in the gaps with new components’. The main advantage of this was having more time to concentrate on software coding that directly addressed the research problem. Recent researchers such as Calvet and his colleagues (2002) support the VIRCON conclusion that the ready availability of Microsoft tools amongst SMEs, provides an ideal platform for rapid software prototyping.

This section considers the development of the VIRCON System from an alternative, idealised, perspective. The purpose of this is to consider whether further development work might be approached in a different manner. The proposed alternative development route is idealised in two ways. Firstly, it has the benefit of prior knowledge about the actual VIRCON System that emerged through many prototyping iterations. Secondly, it assumes that there will be no reliance on third-party software. This assumes that research resources are available to model, specify and develop a new system in its entirety. For example, much of AutoCAD’s functionality of would need to be replicated.
The biggest advantage to this method is that development teams would not be trying to workaround third-party limitations. Any bugs would be completely accessible to programmers.

Where an entire system is being coded from the ground up, it is desirable to move from generalised information models (the client’s ‘real-world’ problem) to automatic code generation. There is also the reverse case, where an existing application is ‘reverse engineered’ back to diagrammatic form. The computer science field of Object-Oriented Analysis and Design has standardised this type of visual representation as the Unified Modeling Language (UML) (Object Management Group 2002). UML is not a mark-up language such as HTML. Instead it is a syntax of graphical symbols and conventions for representing software applications. As a design tool, this allows the required software functionality to be illustrated from a variety of aspects. Ultimately, UML can be used to automatically generate object-oriented programming code, such as C++. However, it is not always used in this way. Sometimes it just provides a common charting language for programmers to describe a system. The latest version of UML is v1.4, also known as ‘formal/2001-09-67’ (Object Management Group 2001). The Object Management Group specification says:

> "The Unified Modeling Language (UML) is a graphical language for visualizing, specifying, constructing, and documenting the artifacts of a software-intensive system. The UML offers a standard way to write a system's blueprints, including conceptual things such as business processes and system functions as well as concrete things such as programming language statements, database schemas, and reusable software components." (Object Management Group 2002).

UML has several "models" or "diagrams" that are used to describe a software system. Each model represents a different aspect:

- The Use Case Model (Diagram) - a particular activity that an actor performs. The emphasis is on *what* a system does rather than *how*.
- The Class Model (Diagram) - this is the static architectural representation of software i.e. classes, values and methods. The Class Model shows *what interacts* but not *what happens* when they do interact.
- The Sequence Model (Diagram) - this describes the flow of messages being passed from object to object. Unlike the Class Model, the Sequence Model represents dynamic messages passing between instances of classes, rather than just a static structure of classes.
- The State Model (Diagram) - shows the possible system states in response to varying user or system generated events.
- The Activity Model (Diagram) - a combination of State Model, Use Case Model and a flowchart.
- The Collaboration Model (Diagram) has a similar function to the Sequence Model. The primary difference is that a Sequence Model illustrates the actual message/request sent and a Collaboration Model shows the effect of one object on another ("user PUSHES button" etc.).
- The Component Model (Diagram) - represents the graphical user interface components and their related messaging architecture.

Microsoft Visual Studio .NET Enterprise Architect includes the ability to reverse engineer Visual Studio projects (Visual Basic .NET, C++, C#, Visual Basic 6.0 and Visual C++ 6.0) into Visio UML class diagrams. It can also generate code skeletons for Visual Basic .NET, C++, and C# from UML. Microsoft Visio Professional 2002 does not feature code generation but it can reverse engineer Visual Studio projects (Visual Basic .NET, C++, C#, Visual Basic 6.0 and Visual C++ 6.0) into Visio UML class diagrams. As an alternative, code generation from Microsoft Visio (or other diagramming tools) can be achieved using a third-party solution, such as Codagen Architect (2002). This generates Java in addition to the standard Microsoft languages produced by .NET Enterprise Architect. The UML Visio-based modelling tools included with Visual Studio .NET are fully described on the Microsoft knowledge base (2002).

The procedure for using Microsoft Visio Professional 2002 to reverse engineer applications into UML static Class Models (classes, values and methods) is reasonably straightforward. For example, in Microsoft Developer Studio using Visual C++ 6.0 the steps are as follows (this assumes Microsoft Visio Professional 2002 is installed) :

- Tools menu->Customize
- Customize dialog box->Add-Ins And Macro Files tab
- Add-Ins And Macro Files list->Visio UML Add-In.
- Visio UML Add-In->check mark
- Click Close
- Visio UML Add-In toolbar appears.
- Dock toolbar by dragging it to the toolbar area (to make sure visible next time)
- Open the Visual C++ project
- Generate a Browse Information file
- Reverse Engineer UML Model toolbar button on the Visio UML Add-In toolbar
- It may take several seconds to extract the class information from the Browse Information file. When the extraction is complete, the Visio UML Model Diagram solution opens with a blank static structure diagram drawing page and a tree view in the Model Explorer, populated with icons that reflect the class definitions in the source code.
- In the Visio UML Model Diagram solution, drag icons from the tree view onto the drawing page to create a static structure diagram that represents a view of the model.

The architecture of the existing VIRCON system has been largely determined by the third-party components. Therefore, there is not much value in reverse-engineering the components as a prelude to improving the architecture. It is possibly more useful to manually deconstruct the functions of the completed system (including the third-party elements) and then redesign the system in UML. The generally accepted sequence for UML software design, is to produce Use Case Models (often with a client) and then use this information to identify objects and hence Class Models. It is common practice to increase the granularity of these UML models, working from the general to the particular. Figures 3 and Figure 4 are early, high-level examples of this process. After further work, it should be possible to generate a skeleton C++ project from the Class Model. The link between the UML Class Model and the code can be maintained after generation. Revisions can be made to the Class Model and applied directly to the code.

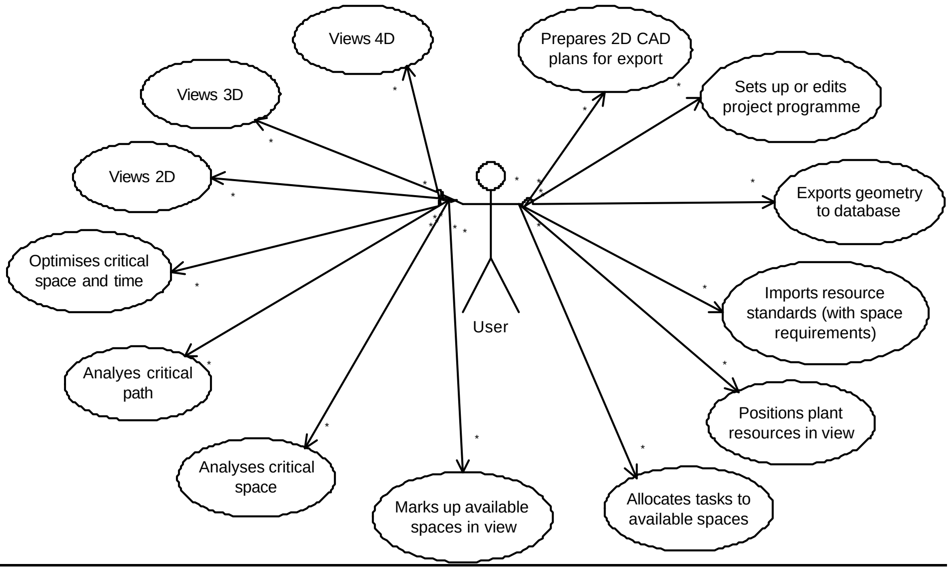

Figure 3 Example high-level UML Use Case Model for VIRCON

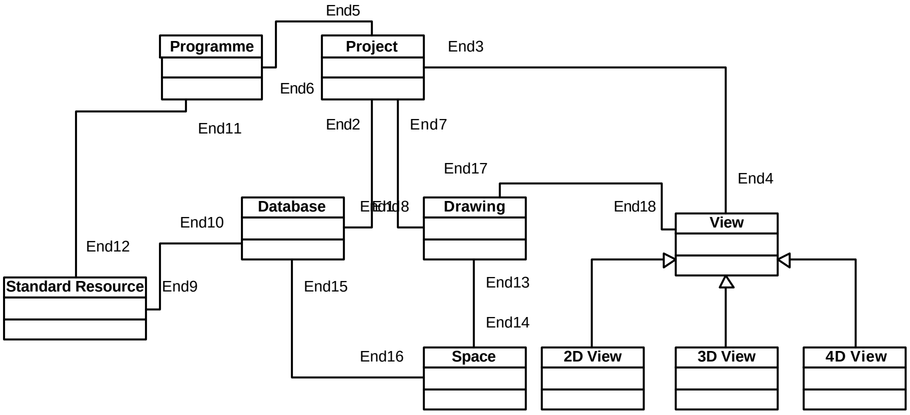

Figure 4 Example high-level static UML Class Model for VIRCON

5: Evaluation of the VCS ‘as recommended’ and ‘as built‘

This section will review the system “as recommended” by the conclusions from our early work in tasks 3 and 4 and compare it with the system as delivered at the end of task 9.

5.1 VIRCON System ‘as recommended’

The following list represents key elements of the VIRCON System ‘as recommended’. This is compiled from Kelsey, Winch and Penn’s VIRCON requirements capture report for Task 4 (2001) and Heesom & Mahdjoubi’s technology potential Task 3 reports (2002a, 2002b, 2002c):

- Microsoft Project should be utilised.
- Templates for plant and temporary works should be included in space layouts.
- A space density or space capacity factor should be included.
- VIRCON should be decision support system rather than an expert system.
- System should generate dynamic simulations of space and time.
- System should be web-enabled.
- System should integrate with other systems used by contractors
- System should be able to receive CAD drawings on CD-ROM from architects in order to reduce initial set-up time.
- Industry Foundation Classes should not be used.
- the system should be a “quick and dirty” (QUAD) one, making the maximum use of existing technologies that are already widely diffused, rather adopting theoretically ideal approaches which are, as yet, not implemented in practice.

5.2 VIRCON System ‘as built’

- Microsoft Project 2000 was utilised for project planning and space allocation.
- The PlantMan component allows plant and temporary works templates to be included in space layouts.
- A space capacity factor was addressed in the development of Critical Space Analysis.
- The System maintains a balance between decision support and expert functionality.
- The System generates dynamic 3½D visualisations in both VRML and AutoCAD using the SpaceVis and ProVis components respectively.
- Some elements of the System are Internet-enabled. For example, SpaceMan and AreaMan can work remotely from SpaceMan Server.

- Utilising standard third-party tools, such as Microsoft Access, allows greater compatibility with tools used by contractors.
- The System is able to work with standard CAD drawings, received by the planners on CD-ROM from architects.
- User evaluation showed ease of use and ready comprehension of the potential of the system.

Figures 5 and 6 show the architecture of the delivered system in terms of the set-up phase and the analysis phase. If these are compared with the VIRCON vision shown in figure 1, it can be seen that the system as originally proposed has been largely delivered, even if the precise architecture is somewhat different. The set-up phase architecture in figure 5 shows the way in which the VIRCON database is at the centre of the VCS, taking inputs from CAD and CPA software, as well as our own ResourceMan tool to store process planning information. This is then enhanced through methods information input using PlantMan, and identification of available spaces using AreaMan.

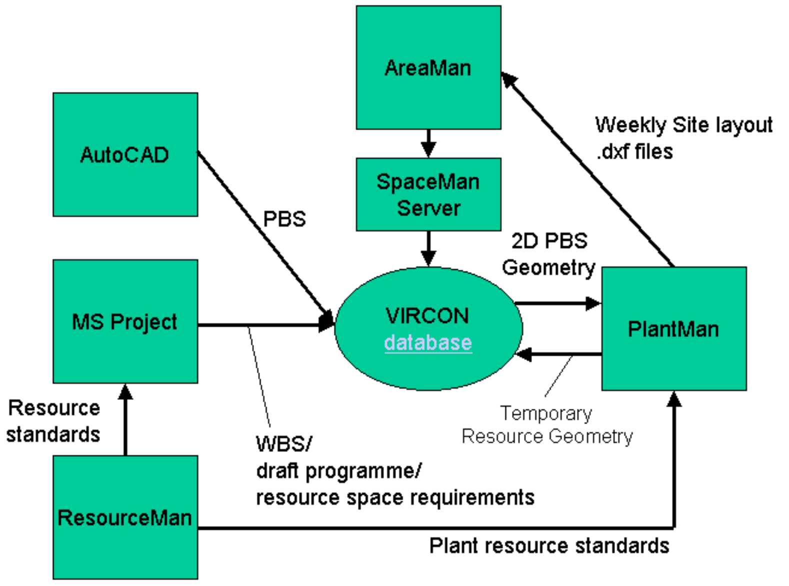

Figure 5 VIRCON System Set-up Phase
source : North and Winch (2003)

Moving on to the analysis phase shown in figure 6, SpaceMan Client provides the space-time broking capability within the VCS. Visualisation is provided using two different approaches – SpaceVis operates in a VRML environment to provide simple visualisations of the basic spatial issues on the project, including plant movement paths. ProVis operates within AutoCAD, providing a more detailed visualisation of the progress of the project “extruded” up from the 2D CAD inputs to the VCS. This process of extrusion results in what is sometimes known as 2½D (e.g. McCarthy 1999), to distinguish it from a true 3D wire frame or solid model. Such models have the considerable advantage that they require much less work in building the original CAD model, and are appropriate where a 3D model is not justified for other reasons, such as analysis of product performance. Our programme visualisation model has, therefore, been dubbed a 3½D visualisation tool, to distinguish it from current true 4D approaches. ProVis is also capable of visualising critical spaces by using colour coding, an approach that is being developed in the doctoral work by Mallasi.

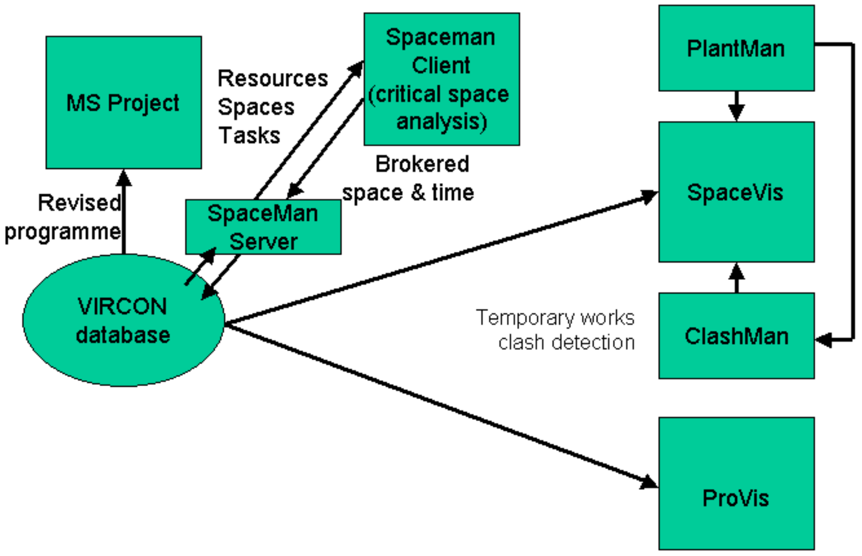

Figure 6 VIRCON System Analysis Phase
Source North and Winch (2003)

6: Evaluation of the VCS Against the Current State of the Art in Construction IT

Since the review of the state of the art in construction IT reported in Heesom and Mahdjoubi (2002a,c), it has – perhaps inevitably - moved on. The two main technical developments are the widening diffusion of industry foundation classes (IFCs), and eXtensible Markup Language (XML). This section will review the implications of these two developments for the VIRCON research project.

6.1 Industry Foundation Classes

At research commencement, IFCs were starting to be used in research and pilot implementation environments, but we believed that to attempt to make the VCS fully compatible would be a diversion from our QUAD approach derived from our requirements capture work. However, there are substantial and growing efforts directed towards information standardisation and integration under the direction of the International Alliance for Interoperability (IAI). This is an industry association dedicated to embracing standardisation and develop tools associated with it. The objective is to provide a universal basis for process improvement and information sharing in the construction and facilities management industries. A number of IFC development projects are now working hard to complete their work in time for inclusion in the IFC 2x Edition 2 release proposed for Spring 2003. Their inclusion will mark the largest ever increase in functionality for the IFC model and will expand its capabilities into areas where there is a known demand for high quality information exchange.

At the time of the start of database development for the VIRCON project during 2000, none of the industrial data that the researchers were aware of in the UK was IFC compatible and there was no stable IT tool that supported IFC 1.5.1, which was the current release at that time. Moreover, IFC 1.5.1 mainly supported building *product* data and not other types of data, for example, process, spaces, and the like. As the VIRCON database is mainly populated with live data from the University of Teesside's Centuria building, a relational database approach provided perfectly adequate capabilities to store and query information regarding process, products, resources, spaces, and the like. It should also be noted that the process of preparing building drawings and modelling building in IFC is quite different compared to the current methods of drafting 2D and 3D drawings. It would have take enormous amount of time – we estimate about 6 months - to redraw the Centuria Building product data and it would have been difficult to justify this to the industrial collaborators, given the proposed objectives of the research.

Looking at the future, the IFC standard keeps improving and immediate release of IFC 2x2 and IFC 3 (expected in 2-3 years) should enhance the capabilities of IFCs and encourage the industry to use them. Furthermore, the database tools for IFC are improving and been developed using SQL servers, with which the VIRCON database is fully compatible.

The development of the VIRCON system did not ignore the IFC standard, however. Several trials were conducted using the currently available standards and tools. These developments includes:

- The deployment of Uniclass/ISO 14177 which is the UK classification standard for structuring product, process, and resource data. This standard obviously is supported by the IFC called IFCClassification.
- The development of ProVis, a 3½D visualisation tool, as a plug-in to Architectural Desktop 3.3. This tool can be used to visualise an IFC based product model (Dawood *et al* 2003b).

In conclusion, the research team believe that the right approach was used in the project and VIRCON tools can be further developed to cater for IFC standards. This obviously will depend on the level of industrial support for IFC.

6.2 XML

Since the start of the VIRCON research, eXtensible Markup Language (XML) has reinforced its position as a realistic technology for implementing information models. Recent construction industry researchers, such as Katranuschkov et al. (2002), have described XML as the 'glue' between users and data. Whereas three years ago at the start of the VIRCON project, XML would have been just one of several choices for developing interfaces and data maps, it is now clearly emerging as a standard. It is becoming increasingly common to combine XML with IFC technology. Adachi (2002) provides an excellent description of implementing a project database server using both of these technologies.
XML has been widely adopted for construction software development. However, there are no clear leaders in terms of the many construction-specific XML dialects (for example bcXML).

The key element of XML is its ability to separate raw data from presentation format. The implication of this is that the either the data or the format can be revised without the need to change both. XML has a variety of specifications, the main one - *XML Specification v1.0 (2nd Edition)* (W3C 2000) - describes the overall syntax for creating documents with data-specific tags.

A secondary element of XML is its use to create XML subsets (or dialects) for particular implementations. XML allows its tags to be named and ordered (within syntactical limits) as required by the user. However, there are sometimes advantages to agreeing a set of tags that may be applied to a specific task or industry. This is called a 'schema'. XML documents can then be validated against a schema, to ensure their compliance with the requirements of a particular domain. The schema does not contain any data itself; it simply provides the tag names and structure that are permissible within an XML document in this domain. Schemas provide both an information design reference for developers addressing data exchange issues and a more literal 'run-time' validation, if required.

XML documents can be required to compare themselves with the schema at run-time to check for compliance. This might prove particularly useful where XML documents are generated 'on the fly'. It is important to understand that it is perfectly possible to use XML without schema validation. The schema itself is a separate document, similar to an XML document but without any data. Confusingly, two standards have emerged for defining schemas. The first of these, Document Type Definition (DTD), appeared as a part of the original XML 1.0 specification. This allowed a developer, or standards body, to specify the XML elements, attributes, structure and nesting to be used in a particular type of XML document. This is sometimes also called the 'content model'.

If an XML document conforms with the content model defined by a DTD, it is said to be valid with respect to that DTD. DTD is slowly being replaced by XML Schema (W3C 2001b and 2001c). This is an ongoing effort by the W3C to supplant DTDs with a more flexible and powerful system to describe the structure of conforming XML documents, including provisions for defining datatypes. XML, DTD and XML Schema all relate to data handling. As previously stated, the strength of XML is in the separation of data and format. XML may be used for data exchange between all types of applications (not just HTML web pages). Where XML is used on the web, formatting is handled by the eXstensible Stylesheet Language (XSL). XSL (W3C 2001a) describes how the XML data is laid out on the page. It is possible to have different XSL documents for the same XML data, allowing layout variations. Although, there are various ways to structure the components of an XML web page, the simplest example follows. There is one HTML page (say index.html). This page does not contain any data or formatting. It just references and loads both the XML document (say data.xml) and the format (say format.xsl). In addition, the XML document (data.xml) may be required to validate itself against either a DTD (say schema.dtd) or increasingly an XML Schema document (say schema.xsd).

There is one other relevant specification, eXtensible Stylesheet Language Transformation (XSLT- W3C 1999). This is a programming language (similar conceptually to JavaScript) that allows XML documents to be transformed dynamically. For example, XSLT might be embedded in the HTML page, manipulating XML data in response to user-input.

7: Evaluation of the VCS Against the State of the Art in Construction Project Planning

Following on from comparing the VCS system as delivered to the state of the art in construction IT, this section compares it to a number of different developments in construction planning. These are 4D planning; constraint optimisation; construction space planning, and developments in project planning methods. The section will close with a discussion of some of the implications of the VCS approach as a broader contribution to debate.

7.1 4D Planning software tools

With the emergence of 4D CAD as a tool to assist the visualisation of construction project plans, various software packages have been developed. However most of these concentrate on the utilisation of 4D CAD as a visualisation tool, rather than something that can be used for analytical purposes. Typically, they build the product breakdown structure (PBS) through time, rather than visualise the progress with the work breakdown structure (WBS), and are, therefore, dumb with respect to process. The 3½D visualisation tools developed in the VIRCON project are an interface to allow the construction planner to visualise space usage at various points during the programme. This section presents a technical review of existing 4D visualisation software packages with the 3½D visualisation packages produced during the VIRCON project.

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

Once the CAD and schedule information is imported or linked to the simulator, animations can be generated through associating CAD objects to schedule activities. This association is undertaken manually by the user, using various relationships including one-to-one, one-to-many or many-to-many.

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

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

Project Navigator 2000 – VirtualSTEP
The software is a browser-based application providing the ability to dynamically link schedule information and AutoCAD based drawing objects to present a simulation of the construction schedule. The software utilises a central control panel as an addition to the standard Internet Explorer browser. From here, schedule and CAD information can be entered and the critical path of the schedule can be analysed using a CPM engine. In addition to this, the user also has the ability to input resources and costs to monitor these as the project progresses.

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

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

Common Point 4D

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

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

Visual Project Scheduler

VPS can import various 3D .dxf files into a common database so that objects can be reviewed. Objects in the overall model can then be broken into parts and regrouped as construction objects. The colour of objects or pieces of those objects can be changed to display specific meaning. Using an ‘Activity Wizard’, activities can be generated automatically for all 3D objects in the model by selecting objects in the sequence of construction. The number of labourers and a calculated duration will be automatically assigned if the object is assigned a construction class.

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

An overview of the performance of these systems compared to SpaceVis and ProVis is provided in table 3. A more detailed analysis can be found in Dawood et al (2003b).

Name	Add in to existing CAD package	Standalone package	Manual linking of product process	Formalised PBS – WBS linking	Type of CAD data required	IFC compliant	Planning software supported	Visualisation medium	Web enabled	Real time updates of task 3D model	3D Product Object Grouping	Real time Navigation of 3D Environment
Bentley Schedule Simulator	No	Yes	Yes	No	Microstation	No	Primavera	Internal Bentley 3D Format	No	No	Manual	No
Common Point 4D	No	Yes	Yes	No	AutoCAD	Yes	MS Project Primavera	VRML, 3D Studio, Macromedia Shockwave, AutoCAD .dwg format	No	Yes	Manual	Yes
SmartPlant Review	No	Yes	Yes	No	VR 3D objects (VRML)	No	MS Project Primavera	Internal 3D Format	No	Yes	Manual	No
Project Navigator	No – Add in to Web Browser	Yes	Yes	No	3D VR Objects (VRML)	No	None	VRML	Yes	No	Manual	Yes
FourDviz	No	Yes	Yes	No	3d CAD data (.dxf)	No	None	Internal 3D Format	No	Yes	Manual	Yes
Visual Project Scheduler	No	Yes	Yes	No	.dxf	No	None	OpenGL	No	No	Manual	Yes
Vircon SpaceVis	No	Yes	No	Yes – Uniclass	2D .dwg, .dxf	No	MS Project	VRML	No	No	Manual	Yes
Vircon ProVis	Yes – AutoCAD	No	Yes	Yes – Uniclass	2D .dwg, .dxf	No	MS Project	2½D AutoCAD .dwg format	No	No	Manual	No

Table 3 VIRCON System Compared to 4D Planning Packages Currently in Use

7.2 Multi-constraint Optimisation for Construction Project Scheduling

Sriprasert and Dawood (2002) classify construction constraints into four major groups, which include:

(1) Contractual constraints – time, cost, quality, and special agreements;
(2) Physical constraints – technological dependency, space, safety, and environment;
(3) Resource constraints – availability, capacity, perfection, and continuity;
(4) Information constraints – availability and perfection.

Despite this classification of construction constraints, all previous studies in the domain of construction scheduling and optimisation appear to consider and model the problem as a trade-off between a limited set of constraints. Examples of these classical problem models are the time-cost trade-off, resource allocation, and resource levelling problems. Recently, a new problem of time-space trade-off is becoming an important area of research in the construction industry.

The SpaceMan tool uses a "brute-force algorithm" A brute force algorithm is a systematic search strategy that does not use information about the problem to help direct the search (Bigus and Bigus 2001). 'Brute-force' simply means that every solution is attempted, even if logic precludes it as the goal state. It is the starting point for finding any solution before a more refined algorithm can be designed. It is a simple algorithm that requires no pre-processing phase yet requires a huge number of steps (perhaps an unfeasibly large number of steps) to complete. However, the simplest algorithm (i.e. brute-force) is sometimes the best. A good example is the victory of chess computers over grand-masters. This tends to be achieved by a 'brute-force' assessment of every move, rather than an 'intelligent' programme that more closely simulates human strategy. After all, throwing processor cycles at problems is what computers are good at.

SpaceMan's 'brute-force' algorithm attempts to find an optimal solution by throwing the power of the computer at the problem, rather than designing a more elegant search strategy. In the 'Auto-optimisation' feature, it tries less drastic solutions initially and then moves on to modifications that may impact other tasks or resource allocations. In short, it tries permutations of task dates and spatial requirements until either a solution is found or in-built limits are reached. If it finds a solution, a message box will appear. The usual outcome is an improvement but some tasks are left overloaded. When the auto-optimisation fails, it always resets the changes that it has made to the original values (North and Winch 2002).

The steps for SpaceMan's auto-optimisation are as follows:

Optimise without changing resources :

1. Move task start and end dates within constraints of task earliest and latest start dates;
2. Move task start and end dates within constraints of space creation/destruction dates;
3. Move task start and end dates without constraints.

Optimise by changing resources :

4. Shorten task durations;
5. Reduce task spatial requirements without changing task start and end dates

Previous studies of construction space planning using constraint optimisation, such as Zouein and Tommelein (1999); Elebeltagi *et al* (2001); Zouein *et al* (2002); and Mawdesley *et al* (2002), all focus on schedule-dependent site layout planning rather than the dynamic planning of task execution space. More intelligent algorithms such as genetic algorithms are employed in those studies. The SpaceMan project is, so far as we are aware, the first attempt to optimise jointly the problem of critical path and critical space dynamically, and, therefore, we believe that the use of a simple brute-force approach is justified. There are, however, limitations to this approach :

- The brute-force algorithm is widely criticised for its absurdly inefficient processing time especially for the size of real world construction scheduling problem. It should be noted that for a problem of 15 activities of which each activity has 15 scheduling alternatives, the size of the total search space already yields 1,307,674,368,000 possible solutions. Future research should address this problem by developing more intelligent algorithms for the optimisation of critical time and dynamic working space problem.
- Instead of allowing the algorithm to move task start and end dates without reference to CPA dependencies and shorten task durations, future research could maintain the relationships and consider the optimisation as the negotiation between extension of project duration and degree of space overload.
- The algorithm used in SpaceMan does not aim at arriving at the optimum solution but simply suggest one of the feasible solutions.

Genetic algorithms (GA) are stochastic search techniques based upon the mechanism of natural selection and population genetics (Goldberg 1989). Unlike the brute-force algorithm that simply attempts at evaluating every possible solution, GA employ a random, yet directed, search inspired by the process of natural evolution and the principles of “survival of the fittest” for locating the globally optimal solution and therefore significantly reduces searching time and becomes feasible for the real world problems.

Several studies have successfully applied GA for optimisation problems in construction scheduling, for instance, time-cost trade-off problem (Feng *et al* 1997; Li *et al* 1999; Que 2002), resource allocation and levelling problem (Hegazy 1999), and a combination of these two problems (Leu and Yang 1999). However, none of these efforts has been able to simultaneously solve and optimise the four groups of construction constraints identified earlier. There is, therefore, a great need to develop a practicable GA-based application that is particularly capable of optimising such the complex problem. This is the subject of current doctoral research by Sriprasert.

7.3 Developments in Construction Space Scheduling Research

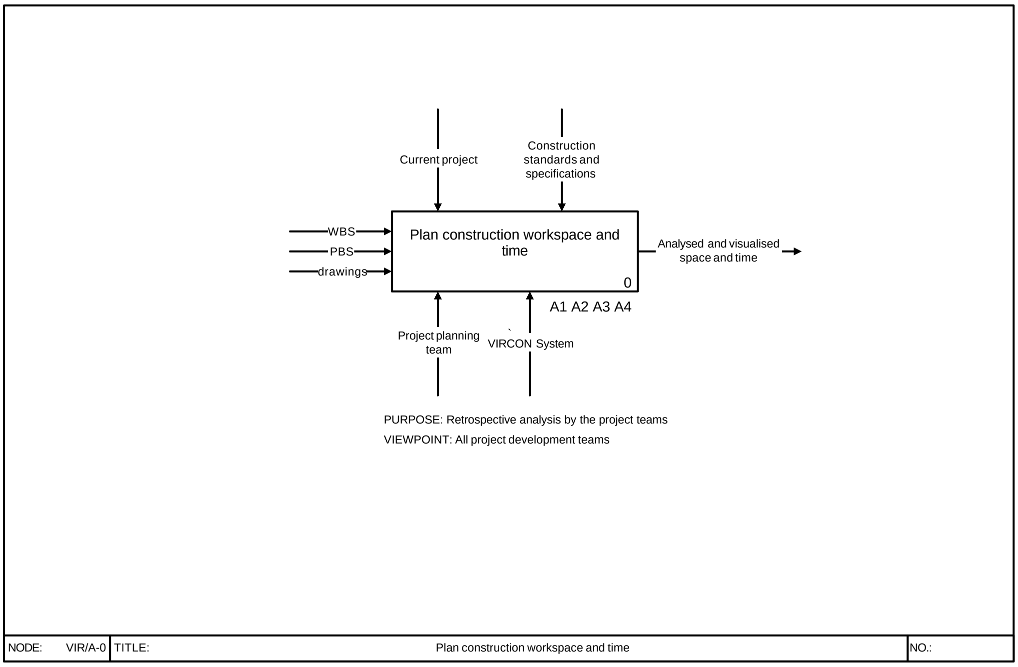

Figure 7 Level 0 IDEF Diagram for VIRCON System
Source : North and Winch (2003).

The aim of this section is to review the research to date on the dynamic space scheduling of construction projects, thereby showing how the VIRCON system contributes to knowledge in this area. The space scheduling problem is distinguished from the site layout problem (Akinci *et al* 2002b), which is focused on the location of temporary facilities of various kinds. There is now a significant body of work on the site layout problem. The work of Tommelein at Berkeley, coming from an operations research perspective, is perhaps the best known contribution here (e.g. Tommelein *et al* 1990). Her work on

SightPlan its derivatives represents a sustained attempt to apply the latest modelling techniques to the problem. Much of the recent work relies genetic algorithms for analysis (e.g. Elbeltagi *et al* 2001; Mawdesley *et al* 2002; Tam *et al* 2002; Tawfik *et al* 2002; Zouein and Tommelein 1999; Zouein *et al* 2002). Others such as Cheng and O'Connor have used Geographical Information Systems (GIS), while Retik and Shapira (1999) have applied Virtual Reality (VR) techniques to this problem.

There is relatively less work on the space scheduling problem. In order to complete the process shown in figure 7, a variety of different functions have to be provided by the space scheduling system. Table 4 provides an indicative comparison of VIRCON functionality with other recent research outputs. The numbers in the headings relate to these functionality criteria :

1. *Import programme information*. This is typically takes the form of a work breakdown structure (WBS i.e. the schedule of all tasks that need to be executed for the building to be completed) arrayed in a critical path network. This provides data on **t**.
2. *Import product information*. This is typically in the form of a product breakdown structure (PBS i.e. the schedule of all components that make up the completed building) arrayed in a spatial configuration. This can be in 2 dimensions, providing data on **x** & **y**, or 3 dimensions providing data on **x**, **y**, & **z**.
3. *Import facilities information.* The term "facilities" is used generically to encompass spatial data on the site installations, access platforms, lay down areas, movement paths and the like.
4. *Import resource information.* A library of the spatial requirements of task execution and associated materials storage, plant operations and the like needs to be available.
5. *Identify available spaces at the level of the planning period*. This cannot be done directly from the data at 2, because many of the product components will not be placed for most of the project life-cycle. A tool is required for manipulating product data to identify its process relevance.
6. *Populate available spaces with facilities information*. Overall site layout needs to be determined, and its evolution at the level of the planning period shown. This could include the output of site layout analysis.
7. *Relate the planned sequence of tasks to the available space.* This function is at the heart of any space scheduling tool, relating 1, 2, 3, 4, 5 and 6. Unless this is provided in an easy-to-use manner, then any other functionality is unlikely to be used by planners.
8. *Identify spatial clashes*. These can be between spaces occupied by different resources, or between resources and completed elements of the product. This functionality implies some sort of automation of

reporting. Where clash detection is achieved purely through visualisation, then the functionality is included at 9.

9. *Visualise schedule information in terms of space and time.* Whether this is done in 3D (x, y + t) or 4D (x ,y ,z + t) will depend on the inputs at 2.
10. *Resolve spatial clashes.* Functionality can be provided to propose solutions to any clashes identified at 9.

A fully specified system would handle all these functions in an IT environment, taking data seamlessly from the appropriate input data sets, and allow analysis and visualisation within that environment. In table 4, this criterion is 11 - level of IT integration. As discussed in section 5, our requirements capture phase also identified the importance of good integration with existing systems in use by construction planners, and the data formats currently used by architects. In table 4, this criterion is 12 - level of system integration. A third issue is the planning horizon used – in essence whether the tool is a strategic planning tool at the weekly level or above to support approaches such as Last Planner, or it attempts to plan at the level of the day or less. This is criterion 13. We now turn to the individual contributions to research in spatial scheduling, and attempt to evaluate them against these criteria.

Following the pioneering work on defining the problem and categorising space use types, Riley and Sanvido (1997) developed a methodology for spatial planning on construction sites, and then applied it to detailed planning using data collected from interviews. The methodology is captured in IDEF0 diagrams for the process "create construction sequence" which contains four sub-processes : identify required spaces; generate layouts; sequence activities; and resolve conflicts. The outputs from each of these steps are displayed graphically. The methodology is focused on detailed planning at the daily activity level, and the data are taken from empirical cases, although the methodology was not used for actual planning on the live projects.

There are a number of limitations to this approach :

- The methodology is not supported by any IT ;
- It is not clear what the source of spatial information is, either in terms of available space or amount of required.
- Planning is at the daily level despite comments by more than one informant that formal planning at this level of detail was not appropriate;
- Only the areas enclosed by the envelope of the completed building are used in analysis.

Thabet and Beliveau, the source of the algorithm for analysing spatial loading, also propose a method for analysing available space (1994). They first determine the physical spaces available, suggesting that this can be done within a CAD program. These are then broken down into work blocks; and activities allocated to these work blocks. Again, there are important limitations here :

- The methodology has very little support from IT tools – all tasks are carried out manually, except for the calculation of spaces in the completed building;
- The sources of inputs 1 and 2 are unclear, while 3 relies upon the product model of the completed building. The definition of work blocks appears to be manual;
- Planning is at the daily level.
- Only the areas enclosed by the envelope of the completed building are used in analysis.

Guo (2002) presents a method for analysing spatial clashes. He proposes marking up CAD drawings produced in AutoCAD with spatial requirements for task execution, storage, temporary works and paths. Presumably, marking up is done within AutoCAD itself. By marking up the blocks of required space on the drawing, spatial clashes can be identified, and daily workplans thereby amended. This approach has some important limitations :

- There is little support from IT tools – 2D plans of the completely building are simply marked up, so it is only a partial solution to 3.
- It is not clear how the MS Project input is manipulated to solve 6
- 2 D Visualisation is handled within AutoCAD.
- The approach is planning at the daily level or below.

Akinci and her colleagues (2002a; 2002b) have developed a full 4D approach to planning the use of space in site. Working from a 4D model, she captures spatial requirements at the microlevel for the installation of a given PBS element (component) through a user interface. This data are then manipulated to allow the process space and product space to be related. The user interface specifies spatial constraints – calculation of the spaces within the 4D model is then automated. On the base of this data, clash detection and visualisation are then possible. This work is probably the most sophisticated, at least in IT terms, but it suffers from a number of limitations :

- A prior 4D model is required, yet this technology is not widely diffused; indeed, a specific 4D modelling package is apparently required.
- There is, apparently, no direct relationship to the WBS. Unlike most applications where tasks are allocated to spaces, here spaces are allocated to components. This would appear to be counter-intuitive from a planning point of view.

	1	2	3	4	5	6	7	8	9	10	11	12	13
Riley and Sanvido	manual	manual	manual	manual	manual	manual	manual	No functionality	none	No functionality	low	low	daily
Thabet and Beliveau	manual	manual	manual	manual	manual	manual	manual	No functionality	none	No functionality	low	low	Not fixed
Guo	manual	manual	manual	manual	manual	manual	manual	visual	2D	No functionality	low	low	hourly
Akinci *et al*	From 4D model	From 4D model	From 4D model	From 4D model	No functionality	From 4D model	Not applicable	automatic	4D	No functionality	high	low	3 weeks
VIRCON	From MS Project	2D from AutoCAD or .dxf using DataExtractMan	Drag and drop	From ResourceMan	AreaMan mark-up tool	PlantMan tool	SpaceMan tool	SpaceMan tool	3½D	SpaceMan Brute force algorithm	medium	high	1 week

Table 4 VIRCON System Compared to Other Construction Space Scheduling Research

7.4 Developments in Project Planning

This section will discuss some of the principal recent developments in project planning, and relate them to the VIRCON approach. These developments are critical chain analysis, last planner, and project schedule risk analysis.

Critical chain analysis (CCA), evolved from the Theory of Constraints (Goldratt 1998; Goldratt and Cox 1993). Amongst other things, it addresses one of the key problems of Critical Path Analysis – its basic assumption that the resources required for task execution are infinite. Although resource levelling techniques are available witin CPA, CCA goes much further, and places resourcing at the heart of the planning process. In CCM, the *critical chain* is the *longest* resource constrained path through the network, theorised as a constraint to be elevated . Thus a critical chain looks like a critical path, but it includes resourcing in the dependencies – plug-ins for MS Project are available to allow this to be done, such as ProChain. Conceptually, it is straightforward to conceive of task execution space as a constraint analogously to resources.

One of the main problems with managing by deadlines – or more specifically, latest start dates – is that there is a strong tendency to start work even if not all the resources required for the completion of the task are available. These problems have been addressed in more depth by the advocates of "shielding production" through the *last planner* technique (Ballard and Howell 1998). They argue that the key to efficiency is shielding task execution so that tasks only start when precedent tasks have been completed, and all the resources are available. Such ready-to-start tasks are known as "quality assignments". The approach is called last planner because making quality assignments is the last stage in the project planning process. The planning horizon is typically one week, and the decision-making process is delegated down to the level of first-line supervision. Again the conceptual link to CSA is straightforward – the availability of required space which is not overloaded (i.e. $s < 100$) is a component of a quality assignment.

The analysis of schedule risk within traditional CPA approaches has also developed recently, with the availability of tools such as PertMaster, the risk module of which can also read MS Project files. Project risk analysis tools analyse assigned probability distributions for each task in the network and at the level of the network as a whole using Monte Carlo simulation. Such analysis is valuable for understanding the likelihood of achieving the agreed project end date, and for identifying tasks which might lie off a deterministic critical path, but which have a significant chance of becoming critical should they end late. In principle, a similar approach could be applied to space-time broking, where the probability of a critical space being available for the planned task execution could be analysed. However, the interactions between space, time and the availability of resources raise the risk analysis problem to a new level of complexity which should not be underestimated.

7.5 Issues in the VIRCON Approach

The VIRCON database is populated with simple 3D product geometry represented by the BoundingBox co-ordinates of each component in the PBS. The main mechanism for applying Critical Space Analysis (CSA) in the VIRCON system relies on the 2D geometrical information input from the project database, as annotated within AreaMan and PlantMan. At the core of CSA analysis lies SpaceMan and its optimisation algorithm for minimising spatial overloads. Clearly, an evaluation of the potential limitations of this 2D approach to spatial analysis is necessary, as many authorities advocate a 3D approach. It is the assertion that spatial planning on construction sites is, in essence, a 2D + **t** problem that allows the QUAD approach to be justified.

Planners currently work with 2D plans of the completed building when planning spatial use on site – this is all that is currently available to them – and they typically mark them up by hand. What might be the advantages of providing an ability to plan in 3D? Users might wish to have the sense of the 3D space and check if the plant headroom is not conflicting with the roof/upper floor level. Another is that the analysis only retrieves the x and y co-ordinate values from the database of the 2D areas marked-up by AreaMan (horizontal analysis). Though the system can recognise simple intersections between marked-up areas, it can only handle intersections between elements sharing the same z value (i.e. on the same floor level). This limits the system in the recognition of vertical conflicting spaces (vertical analysis) such as ceiling level activities (e.g. a/c ducting) and floor level activities (e.g. floor tiling). Such cases could well benefit from a full 3D analysis.

However, we suggest that such advantages are relatively marginal, and unlikely to warrant the additional cost of developing full 3D analysis in the absence of a 3D model being available directly from the designers. For a given **z** level of activity – such as a floor of a building – any activity at height is likely to sterilise the space below it for two reasons. Firstly, the access platform for working at height is likely to be founded at the base level, thereby rendering the space below the task execution space unusable. It should be noted here that within PlantMan/AreaMan the task execution space provided by an access platform such as a scaffold is designated as a separate space, and where access is provided by a mobile platform, it is simply designated as a plant space. Secondly, even where the simple mechanics of access do not make the base level area unusable for task execution, safety considerations are likely to constrain significantly the ability of tasks to be scheduled one above the other. Where activities are scheduled on tiered base levels, such as on multiple floors, then these are treated simply as separate spaces (z-levels) for task execution planning. Perhaps the main area where 3D would offer an advantage is in identifying plant movement clearances in the z dimension.

8: Possible directions for future research

The Task 9 report on systems integration (North and Winch 2003) identified a number of areas of future activity, divided into system development activity, system limitations, and future research themes. With the aim of suggesting possible areas for fruitful exploration, this section reprises the limitations (LIM) and research themes (FR) from that report.

VIRCON Database

1. To comply with Industry Foundation Classes (IFCs) (FR).
2. To facilitate processes of Uniclass implementation (FR).

ResourceMan

3. To research the representation of space requirements of both human resources and plant resources. The challenge is to find more appropriate ways to represent or to suggest acceptable values for requirements of work area, unloading area, staging area, storage area, hazardous area, and paths (FR).

ClashMan

4. To suggest ways to remove clashes (FR).

AreaMan

5. To research the need for AreaMan as a mark-up tool. A few users suggested that the system should be able to automatically identify weekly available spaces after all plant items and their associated required areas and paths are allocated in the project model (FR).

SpaceMan

6. Visualisation of space and task allocation (FR).

General

7. It was originally envisaged that stage one of the VIRCON process would be the CAD Operator preparing the plans and then exporting the PBS to database. Stage two would be the planner working from the drawings to produce a draft programme in MS Project. However, it was realised that the CAD Operator requires the programme in order to group products in AutoCAD (see Dawood et al. 2003b, Appendix A). These groups represent work packages and are used by ProVis to display the 3½D sequence (LIM).

9: Conclusions

The VIRCON project has delivered very much what it set out to deliver – a proof of concept of a system to support construction planners in planning the sequence of tasks and the spaces in which they will executed on site in a interactive manner. User evaluation of the system by a number of experienced planners has shown that the delivered VCS has significant potential. Our aim was not to push forward the boundaries of construction IT for their own sake – this was a requirements led research project. We willingly adopted a QUAD approach, making the maximum use of existing technologies because this allowed us to meet our objectives of improving the construction planning process more effectively.

Building on earlier work – particularly that done in the USA – we have developed the theory of critical space analysis and implemented it by developing software tools that, with further development, will soon allow construction planners to plan space use on site with as much software support as they presently have for planning the sequence of tasks through time. Based on the VIRCON database, tools such as ResourceMan, AreaMan, PlantMan and SpaceMan all provide the sort of functionality that modern planners – facing ever tighter programmes and more demanding clients – need. The communication of these programmes to clients and other stakeholders will be enhanced by the visualisation tools integrated into the VCS – SpaceVis and ProVis. These are relatively simple to use, and allow the cheap, quick and, above all, smart visualisation of the programme.

The VIRCON dissemination programme (task 11) is currently under way. In addition to conference papers already delivered and journal articles in preparation (e.g. Dawood *et al* 2002; Winch 2002; North and Winch 2002b; Winch and North 2003), regional industry seminars are being planned in collaboration with appropriate bodies, and a national meeting is also planned for the autumn.

References

Adachi, Y. (2002) Overview of IFC model server framework *eWork and eBusiness in Architecture, Engineering and Construction, the proceedings of the fourth European conference on product and process modelling in the building and related industries (ECPPM 2002* Turk & Scherer (eds.), Portoroz / Slovenia, Rotterdam: Balkema pp.367-372.

Akinci, B. Fischer, M. Kunz, J. and Levitt, R. (2002a) Representing Work Spaces Generically in Construction Method Models *Journal of Construction Engineering and Management* **128** 296-305.

Akinci, B. Fischer, M. and Kunz, J. (2002b) Automated Generation of Work Spaces Required by Construction Activities *Journal of Construction Engineering and Management* **128** 306-315.

AutoDesk (2000) *AutoCAD 2000 DXF Reference (version u15.0.02)* http://www.autodesk.com/techpubs/autocad/acad2000/dxf/index.htm, [accessed January 2002].

Ballard, G. and Howell, G. (1998) Shielding Production : Essential Step in Production Control *Journal of Construction Engineering and Manag*ement 124 11-17.

Bigus, P. and Bigus, J. (2001) *Constructing intelligent agents using Java* Wiley & Sons, USA.

British Standards Institute (1998): *BS 1192-5:1998 Construction drawing practice- Guide for the structuring and exchange of CAD data*. London, BSI.

Calvet, M., Casals, M. & Forcada, N. (2002) Construction project management tool *eWork and eBusiness in Architecture, Engineering and Construction, the proceedings of the fourth European conference on product and process modelling in the building and related industries* (ECPPM 2002), Turk & Scherer (eds.), Portoroz / Slovenia, Rotterdam: Balkema, pp. 167-170.

Cheng, M. Y. and O'Connor, J. T. (1996) ArcSite : Enhanced GIS for Construction Site Layout *Journal of Construction Engineering and Management* **122** 329-336.

Codagen Architect (2002) *Features of Codagen Architect* http://www.codagen.com/products/architect/features.htm [accessed December 2002].

Crawford, M. Cann, J. and O'Leary, R. (1997): *Uniclass- Unified classification for the construction industry*, London, RIBA Publications.

Dawood, E. Sriprasert, E., Mallasi, Z. & Hobbs, B. (2002) Product and process integration for 4D visualisation at construction site level: a uniclass-driven approach *eWork and eBusiness in Architecture, Engineering and Construction, the proceedings of the fourth European conference on product and process modelling in the building and related industries (ECPPM 2002)* Turk & Scherer (eds.), Portorož / Slovenia, Rotterdam: Balkema.

Dawood, N., Sriprasert, E. & Mallasi, Z. (2003a) *Data capture and database development*, University of Teesside, a VIRCON project report.

Dawood, N., Sriprasert, E. & Mallasi, Z. (2003b) *Visualisation development: whole building Visualisation*, University of Teesside, a VIRCON project report.

Dawood, N., Sriprasert, E. & Mallasi, Z. (2003c) *User evaluation* University of Teesside, a VIRCON project report.

Elbeltagi, E., Hegazy, T., Hosny, A. H., and Eldosouky, A. (2001) Schedule-dependent evolution of site layout planning *Construction Management and Economics*, 19, 689-697.

Feng, C.-W., Liu, L., and Burns, S. A. (1997) Using genetic algorithms to solve construction time-cost trade-off problems *Journal of Computing in Civil Engineering*, 11(3), 184-189.

Goldberg, D. E. (1989) *Genetic algorithms in search, optimization and machine learning*. Addison-Wesley Publishing Co., Reading, MA.

Goldratt, E. M. (1997) *Critical Chain* Great Barrington, The North River Press

Goldratt, E. M. and Cox, J. (1993) *The Goal (2nd ed.)* Aldershot, Gower.

Heesom, D. & Mahdjoubi, L. (2002a) *Technology opportunities and potential volume 1: emerging research initiatives*, University of Wolverhampton, a VIRCON project report.

Heesom, D. & Mahdjoubi, L. (2002b) *Technology opportunities and potential volume 2: project planning software*, University of Wolverhampton, a VIRCON project report.

Heesom, D. & Mahdjoubi, L. (2002c) *Technology opportunities and potential volume 3: enabling technology and potential*, University of Wolverhampton, a VIRCON project report.

Heesom, D. & Mahdjoubi, L. (2002d) *Visualisation development*, University of Wolverhampton, a VIRCON project report.

Hegazy, T. (1999) Optimization of resource allocation and leveling using genetic algorithms *Journal of Construction Engineering and Management* 125(3), 167-175.

ISO (1998a) *ISO 13567-1:1998 Technical product documentation -- Organization and naming of layers for CAD -- Part 1: Overview and principles* http://www.iso.ch, [accessed December 2002].

ISO (1998b) *ISO 13567-2:1998 Technical product documentation -- Organization and naming of layers for CAD -- Part 2: Concepts, format and codes used in construction documentation* http://www.iso.ch, [accessed December 2002].

ISO (1998c) *ISO/TR 13567-3:1999 Technical product documentation -- Organization and naming of layers for CAD –Part 3: Application of ISO 13567-1 and ISO 13567-2* http://www.iso.ch, [accessed December 2002].

Katranuschkov, P., Gehre, A. & Scherer, R.J. (2002) An engineering ontology framework as advanced user gateway to IFC model data In *eWork and eBusiness in Architecture, Engineering and Construction, the proceedings of the fourth European conference on product and process modelling in the building and related industries (ECPPM 2002)* Turk & Scherer (eds.), Portoroz / Slovenia, Rotterdam: Balkema pp. 269-276.

Kelsey, J., Winch, G.M. & Penn, A. (2001): *Understanding the project planning process: requirements capture for the virtual construction site*, University College London, Bartlett Research Paper Number 15.

Leu, S.-S. and Yang, C.-H. (1999) GA-based multicriteria optimal model for construction scheduling *Journal of Construction Engineering and Management*, 125(6), 420-427.

Li, H., Cao, J.-N., and Love, P. E. D. (1999) Using machine learning and GA to solve time-cost trade-off problems *Journal of Construction Engineering and Management*, 125(5), 347-353.

Mawdesley, M. J., Al-jibouri, S. H., and Yang, H. (2002) Genetic algorithms for construction site layout in project planning *Journal of Construction Engineering and Management*, 128(5), 418-426.

McCarthy, T. (1999) *AutoCAD Express NT* London, Springer.

Microsoft (2001): *Microsoft DAO Overview* http://msdn.microsoft.com/library/devprods/vs6/vbasic/dao360/dahowdataaccessoverview.htm, [accessed December 2002].

Microsoft (2002): *Visually Model Software Applications* Microsoft White Paper http://msdn.microsoft.com/vstudio/techinfo/articles/developerproductivity/modelsoftware.asp, [accessed December 2002].

North, S. & Winch, G.M. (2002a): *Analysing Critical Space and Time : VIRCON Task 5 and 8* Report UMIST, Manchester.

North, S. & Winch, G.M. (2002b): 'VIRCON: a proposal for critical space analysis in construction planning' in *eWork and eBusiness in Architecture, Engineering and Construction, the proceedings of the fourth European conference on product and process modelling in the building and related industries (ECPPM 2002)*, Turk & Scherer (eds.), Portorož / Slovenia, Rotterdam: Balkema pp.359-364.

North, S. & Winch, G.M. (2003): *System Integration: VIRCON Task 9 Report*, UMIST, Manchester, a VIRCON project report.

Object Management Group (2001): *UML Specification v1.4* http://www.omg.org/cgi-bin/doc?formal/01-09-67.pdf.gz [accessed December 2002].

Object Management Group (2002): *Introduction to OMG's Unified Modelling Language* (UML) http://www.omg.org/gettingstarted/what_is_uml.htm [accessed December 2002].

Que, B. C. (2002) Incorporating practicability into genetic algorithm-based time-cost optimization *Journal of Construction Engineering and Management*, 128(2), 139-143.

Tawfik, H., Fernando, T. & Aspin R.A. (2002) A simulation tool for multi-perspective site layout analysis In *eWork and eBusiness in*

Architecture, Engineering and Construction, the proceedings of the fourth European conference on product and process modelling in the building and related industries (ECPPM 2002) Turk & Scherer (eds.), Portoroz / Slovenia, Rotterdam: Balkema pp.193-197.

Retik, A. and Shapira, A. (1999) VR-based Planning of Construction Site Activities *Automation in Construction* **8** 671-680.

Riley, D. R. and Sanvido, V. E. (1997) Space Planning Method for Multistory Building Construction *Journal of Construction Engineering and Management* **123** pp 171-180.

Sriprasert, E. and Dawood, N. (2002) 4D visualisation of multiple construction constraints *Proceedings of the European Conference on Information and Communication Technology Advances and Innovative in the Knowledge Society (eSMART)*, Salford, UK, 182-192.

Tam. C. M., Tong, T K. L., Leung, A. W. T., and Chiu, G. W. C. (2002) Site Layout Planning Using Nonstructural Fuzzy Decision Support System *Journal of Construction Engineering and Management* 128(3), 220-231.

Thabet, W. Y. and Beliveau, Y. J. (1994) Modeling Work Space to Schedule Repetitive Floors in Multistory Buildings *Journal of Construction Engineering and Management* **120** 96-116.

Tommelein, I. D. Levitt, R. E. Hayes-Roth, B. and Confrey, T. (1991) SightPlan Experiments : Alternative Strategies for Site Layout Design *Journal of Computing in Civil Engineering* **5** 42-63

World Wide Web Consortium (1999) *XSLT specification v1.0* 16 November 1999 http://www.w3.org/TR/1999/REC-xslt-19991116.html [accessed December 2002].

World Wide Web Consortium (2000) *XML specification v1.0 (2nd Edition)* 6 October 2000, available from: http://www.w3.org/TR/2000/REC-xml-20001006.pdf [accessed December 2002].

World Wide Web Consortium (2001a) *XSL Specification v1.0* 15 October 2001 http://www.w3.org/TR/2001/REC-xsl-20011015/xslspecRX.pdf [accessed December 2002].

World Wide Web Consortium (2001b*) XML Schema Specification Part 1: Structures 2* May 2001http://www.w3.org/TR/2001/REC-xmlschema-1-20010502/ [accessed December 2002].

World Wide Web Consortium (2001c) *XML Schema Specification Part 2: Datatypes* May 2001http://www.w3.org/TR/2001/REC-xmlschema-2-20010502/ [accessed December 2002].

Zouein, P. P. and Tommelein, I. D. (1999) Dynamic layout planning using a hybrid incremental solution method *Journal of Construction Engineering and Management*, 125(6), 400-408.

Zouein, P. P., Harmanani, H., and Hajar, A. (2002) Genetic algorithms for solving site layout problem with unequal-size and constrained facilities *Journal of Computing in Civil Engineering*, 16(2), 143-151.