Critical Space Analysis

Graham M. Winch[1] and Steve North[2]

Abstract: The construction space scheduling problem has received relatively little attention from researchers and practitioners. We now have sophisticated methods of planning and analyzing the sequence of tasks within the work breakdown structure through time, but the problem of planning where on site those tasks are to be executed is not well-supported especially as those spaces are dynamic as the project progresses. We know that congestion on site reduces output and generates hazards, yet construction planners presently have to rely upon experience and intuition. The research reported here presents a decision support tool for construction project planners to help them address the space scheduling problem. After a review of recent developments in construction space scheduling, the concept of critical space analysis is presented. This forms the basis of decision support tools presented for marking up available space, allocating tasks to spaces, and analyzing and optimizing space loading in relation to the critical path—what we call space-time broking. Requirements capture and evaluation reports from construction planners suggest that the tools presented here have immediate practical relevance. The paper will, therefore, be of interest to both practitioners and researchers.

DOI: 10.1061/(ASCE)0733-9364(2006)132:5(473)

CE Database subject headings: Construction management; Scheduling; Critical path method; Workspace.

Introduction

Planning lies at the heart of construction project management. The critical path method and its variants have developed into a suite of sophisticated tools for planning the sequence of tasks in the work breakdown structure through time. More recent developments such as critical chain have turned attention to the human resources required for task execution. However, we still lack tools for the effective planning of an equally important aspect of task execution, the space in which the task is to be executed. This paper will introduce the concept of *critical space analysis* and its relevance for construction project planning.

Critical space analysis (CSA) is relevant to that subclass of projects where task execution not only creates the completed facility, but also creates, temporarily, the spaces in which tasks are to be executed. This includes construction, shipbuilding, oil and gas rigs, and process plants. The fundamental planning problem is that task execution space availability is dynamic. First because different trades parade through the same space and may clash spatially. Second because the spaces themselves change as, for instance, floors are laid creating work spaces, and walls are built closing off work spaces. Of course, experienced project planners *do* take into account the availability of task execution spaces, but this is typically based on intuition and rarely formalized beyond the most basic rules of thumb.

[1]Professor, Centre for Research in the Management of Projects, Manchester Business School, Univ. of Manchester, Manchester M15 6PB, U.K.

[2]Research Associate, Dept. of Computer Science, Univ. of Glasgow, Glasgow, U.K.

Note. Discussion open until October 1, 2006. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on May 14, 2003; approved on August 3, 2005. This paper is part of the ***Journal of Construction Engineering and Management***, Vol. 132, No. 5, May 1, 2006. ©ASCE, ISSN 0733-9364/2006/5-473–481/$25.00.

The paper will start by reviewing some important recent developments in construction space planning before the concept of critical space analysis is presented. A review of current research in construction space scheduling follows. An overview of the Virtual Construction Site (VIRCON) project provides the context for the focus on the two main elements of the CSA system—AreaMan and SpaceMan. Conclusions are then drawn. It should be noted that the VIRCON system reported here has no relationship to the construction project simulation tool of the same name developed for teaching purposes by Jaafari et al. (2001).

Development of Construction Space Planning

One distinctive feature of construction projects that distinguishes them from those in many other sectors is that the spaces available for task execution change as the project progresses through the schedule. While the spatial configuration of the production process in a factory remains static during production, the spatial configuration of the construction process is continually changing as, for instance, product elements are fixed, or temporary works are removed. In manufacturing, spatial configuration is usually given considerable attention as the layout of production equipment is planned. Yet in construction, relatively little formal attention is paid to the allocation of tasks to spaces and there are no tools comparable to those available for the sequencing of tasks provided by critical path analysis and its derivatives. The space planning problem in construction has two main elements which are interdependent, but which require rather different approaches. These are the *space scheduling problem*, which is focused on the planning of task execution spaces, and the *site layout problem* 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, from an operations research perspective, is perhaps the best known contribution to the site layout problem (e.g., Tommelein et al. 1991). Her work

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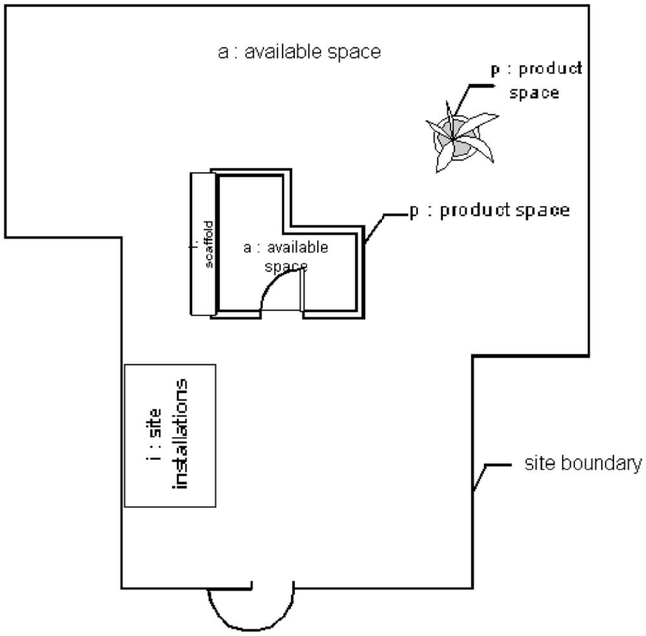

Fig. 1. Construction space classification

on SightPlan and its derivatives represents a sustained attempt to apply the latest modelling techniques to the problem. Much of the recent work relies on genetic algorithms for analysis (e.g., Zouein and Tommelein 1999; Elbeltagi et al. 2001; Mawdesley et al. 2002; Tam et al. 2002; Tawfik et al. 2002; Zouein et al. 2002). Others, such as Cheng and O'Connor (1996), have used geographical information systems (GIS), while Retik and Shapira (1999) have applied Virtual Reality (VR) techniques to this problem. However, comparatively few researchers have turned their attention to the space scheduling problem which is the focus of the research reported here.

Concept of Critical Space Analysis

Resources require space for operation. For example, it has been reported (Thomas and Smith 1990) that studies conducted by Mobil suggest that 19 m^2 per person is required and that 50% more man-hours are required when this declines to 10.4 m^2 which is an absolute minimum. For well-planned emergency labor-intensive short-term tasks, it is possible to manage with 9.4 m^2. Maximum productivity occurs at 30.2 m^2. Other studies confirm 28.3 m^2 as the desirable lower limit effective task execution, and there is evidence that work space congestion reduces productivity (Horner and Talhouni 1995). Similarly, equipment operation requires a working clearance plus a safety zone.

Any analysis of the spatial configuration of the construction process needs a set of definitions of space types. Thabet and Beliveau (1994) pioneered here, while the work of Riley and Sanvido (1995) is authoritative. However, these writers focused on the spaces constrained by the fixing of product elements and did not explicitly consider the total space, as defined by the site boundary. This is, possibly, due to their choice of repetitive multistory building construction as an exemplar. Our proposals here encompass the whole site, and form the basis of the SpaceMan analysis tools reported below. Fig. 1 illustrates our proposed classification, and the main elements are defined in Table 1. Total space is that enclosed by the site boundary, and it is occupied by *product space* taken by fixed product elements such as walls, *installation space* occupied by site installations, prefabrication areas, access platforms, and the like and a balance of *available space*. *Required space* is that needed for effective task execution. This can be the task execution space itself for equipment or operatives, materials storage spaces in support, and movement paths for the supply of resources or the removal of waste.

Table 1. Space Type Definitions

Definition	Space type
Total space	t
Product space	p
Installation space	i
Available space	$a=t-p-i$
Required space	r

Our work focused on *task execution* spaces, as these are the critical ones for construction project planning, and materials storage space and movement paths are a function of these. Critical space analysis (CSA) is proposed as the analysis, optimization, and visualization of the spatial loads placed on a construction project by its scheduled tasks and resources. Spatial loading is the ratio of required space to available space, or what Thabet and Belliveau (1994) call the space capacity factor. A ratio greater than unity means congestion. Critical spaces are defined as those where loading is at unity, i.e., there is no spatial slack. This approach is analogous to critical path analysis (CPA), which is applied to time rather than space, where the critical path is the longest route through the network with no temporal (i.e., schedule) slack. Table 2 gives the key definitions on which CSA is based.

Table 2. SpaceMan Concept Definitions

SpaceMan concept	Definition
Spatial loading	$s=(r/a)\cdot 100$
Spatial overload	$s>100$
Spatial slack	$a-r$ (where $s<100$)
Critical space	$s=100$

Construction Space Scheduling Research

As we developed the concept of critical space analysis from the requirements capture phase (Kelsey et al. 2001; Winch and Kelsey 2005), through software development in interaction with our industrial collaborators (North and Winch 2002) and user evaluation (Dawood et al. 2003c), we identified 10 basic functions any construction space scheduling system must fulfill in order to effectively support the decision-making of construction project planners. These are now discussed in turn, and summarized in Table 3. The numerical headings in Table 3 relate to the function numbers below:

1. *Import schedule information.* This typically takes the form of a work breakdown structure (WBS) and provides a dataset of all the tasks that need to be executed for the building to be completed, often arrayed in a critical path network.
2. *Import product information.* This is typically in the form of a product breakdown structure (PBS) and provides a dataset of all the components that make up the completed building

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Table 3. VIRCON System Compared to Other Construction Space Scheduling Research

Function	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	2D	No functionality	Low	High	Daily
Thabet and Beliveau	Manual	From 3D model	Manual	Manual	Manual	Manual	Manual	No functionality	2D	No functionality	Low	Low	Not fixed
Guo	From MS Project	From 2D plans	Manual	Manual	Manual	Manual	Manual	No functionality	2D	No functionality	Low	High	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 Data-ExtractMan	Drag and drop	From ResourceMan	AreaMan mark-up tool	PlantMan tool	SpaceMan tool	SpaceMan tool ClashMan tool	3 1/2 D	SpaceMan brute force algorithm	High	High	1 week

arrayed in a spatial configuration. This can be in two dimensions, providing data on **x** and **y**, or three dimensions providing data on **x**, **y**, and **z**. This procedure provides data on **p**.

3. *Import installations information.* The term "installations" is used generically to encompass spatial data on site facilities, access platforms, laydown areas, and the like. This could include the output of the site layout analysis approaches identified above and provides data on **i**.
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. This provides data on **r**.
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 on the completed facility to identify its process relevance. This provides **t**-**p**.
6. *Populate available spaces with installations information.* Overall site layout needs to be determined, and its evolution at the level of the planning period shown. This provides **t**-**i**.
7. *Relate the planned sequence of tasks to the available space.* This function is at the heart of any space scheduling tool. Unless this is provided in an easy-to-use manner, then any other functionality is unlikely to be used by planners. This relates the outputs from 1 and 4 to those from 5 and 6 to calculate **s**.
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 visualization, then the functionality is included at 9.
9. *Visualize schedule information in terms of space and time.* Whether this is done in 3D ($\mathbf{x},\mathbf{y}+\mathbf{t}$) or 4D ($\mathbf{x},\mathbf{y},\mathbf{z}+\mathbf{t}$) will depend on the inputs at 2. Where simple marked up plans are visualized, which cannot be played in sequence through time, this functionality is described as 2D.
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 visualization within that environment. In Table 3, this is function 11-level of *IT integration.* Our requirements capture phase identified the importance of good integration with existing systems in use by construction planners, and the data formats currently used by architects. In Table 3, this is function 12-level of process integration. The final element of functionality is the *planning horizon* used, which can vary from less than a day to a month or more. This is Function 13 in Table 3. We now turn to the individual contributions to research in spatial scheduling, and attempt to evaluate them against these functionality criteria.

Following the pioneering work on defining the problem and categorizing 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 subprocesses: 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 space scheduling methodology has very low IT integration;
- It is not clear what the source of spatial information is, either in terms of available space or amount of required space;
- Planning is at the daily level despite reported comments by more than one informant that formal planning at this level of detail was not appropriate; and
- Only the areas enclosed by the envelope of the completed building are used in analysis.

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

- The level of IT integration is very low—all tasks are carried

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out manually, except for the calculation of spaces in the completed building;
- The sources of input 1 is unclear, while 2 relies upon the 3D product model of the completed building. The definition of work blocks appears to be manual; and
- Only the areas enclosed by the envelope of the completed building are used in analysis.

Guo (2002) presents a method for analyzing 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 completed 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; and
- The approach is planning at the daily level or below.

Akinci and her colleagues (2002a, b) have developed a full 4D approach to planning the use of space on 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. These 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 basis of this data, clash detection and visualization are then possible. This work is probably the most sophisticated to date, 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 modeling package is apparently required; and
- There is, apparently, no direct relationship to the WBS. Unlike the other applications discussed in this section, including VIRCON, where tasks are allocated to spaces, here spaces are allocated to components. This would appear to be counterintuitive from a planning point of view.

The VIRCON system has addressed all these areas of required functionality, and Table 3 provides an indicative comparison of VIRCON functionality with other recent research outputs. We now turn to a description of the VIRCON system.

VIRCON System

Our work started with a requirements capture phase, which is reported in Winch and Kelsey (2005). We found that two-thirds of the 18 experienced planners interviewed used some form of phased work location drawings to assist their planning. Based upon a literature review and these interviews, we concluded that any space scheduling system should be:
- A decision-support system, not a decision-making system;
- It should integrate with existing applications and methods in use by planners in what we have called process integration; and
- Its use must be quick and intuitive—planners actually have very little time to plan any one project.

These findings encouraged us to take a "quick and dirty" (QUAD) approach to system development. Our concern was to push forward planning practice, not IT functionality, and so we focused on interoperability between the most widely diffused systems (MS Project, MS Access, and AutoCAD), ease of use, and integration into existing planning practice. The VIRCON system comprises five main functions:
- A *project database* which integrates relevant geometric, method, resource, and task information. This is written in MS Access, and structured according to the UNICLASS standard for construction project information (Crawford et al. 1997) and the BS 1192-5 CAD layering convention. It is capable of taking product data files from AutoCAD (**p**) and program data files from MS Project (Dawood et al. 2003a), thereby fulfilling Functions 1 and 2.
- *Set-up project data tools,* which takes inputs from AutoCAD and MS Project, together with a user interface for inputting standardized required space (**r**) data in ResourceMan (Heesom and Mahdjoubi 2002) which fulfills Function 4.
- *Space planning tools* which allow identification of available space (**a**) data on a weekly basis marked up using AreaMan and the importation of installation space requirements (**i**) using PlantMan's drag and drop capabilities, fulfilling Function 3. Equipment movement paths may also be specified in PlantMan. Spatial clashes between equipment and product spaces can be identified using ClashMan (Heesom and Mahdjoubi 2002; North and Winch 2002).
- Analysis and optimization tools for the analysis of time critical and space critical tasks, and the space-time broking of these two aspects in project planning (North and Winch 2002).
- Visualization tools for the project process with respect to time and space in both VRML (SpaceVIS), and AutoCAD (ProVis). Our current visualization application is 3 1/2 D rather than true 4D because the AutoCAD inputs used are 2D drawings, extruded up from a datum to provide a 2 1/2 D (McCarthy 1999) product model (Heesom and Mahdjoubi 2002; Dawood et al. 2003b). This fulfils Function 9.

Following system integration (North and Winch 2003), the VIRCON system was evaluated in simulations by experienced construction planners (Dawood et al. 2003c) with encouraging results. We now focus specifically on the space scheduling aspects of functionality—Areas 5, 7, 8, and 10 in Table 3—which are the principal contributions of this paper.

Function 5: Identifying Available Space with AreaMan

One of the issues that needs to be addressed is how data on spatial configuration is acquired—Function 2 in Table 3. Thabet and Beliveau (1994) assume that all the spatial definition work will be performed within the CAD system used for the development of the PBS, while Riley and Sanvido (1997) do not address the problem. Guo (2002) marks up existing 2D drawings within AutoCAD, while Akinci (2002a) relies upon an existing 4D model. Our argument here builds on the conclusions of the requirements capture phase (Kelsey et al. 2001) that indicated a clear role for decision support software tools in spatial construction planning. It also meets a need identified during the development of SpaceMan for a simple "mark-up" tool to define available spaces for task execution on a weekly basis. AreaMan is a 2D tool for calculating the areas of spaces in standard DXF CAD files—a screen shot is provided in Fig. 2.

The generation of an available space layer from 2D CAD plans could, in theory, be automated. The programming required to

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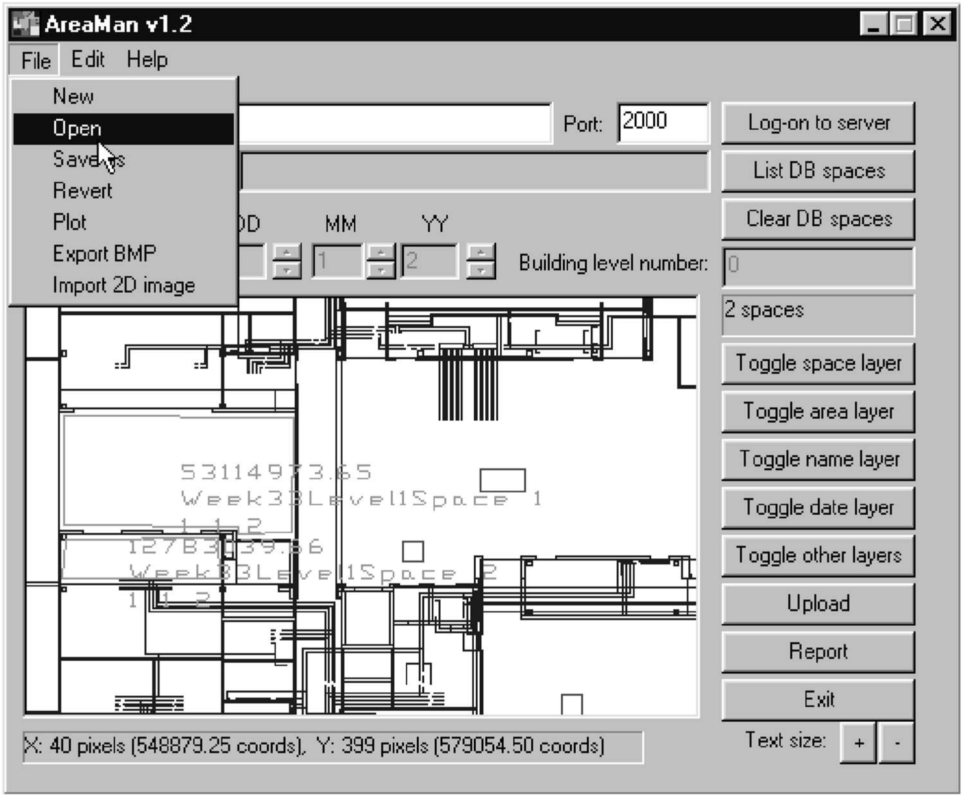

Fig. 2. Screenshot of AreaMan

identify discrete spaces is relatively trivial. Most CAD tools have an internal macro language (for example, Visual Basic for Applications in AutoCAD 2000). It would be possible to write an internal program that would analyze existing CAD layers and generate a new spatial layer. There are three disadvantages with this approach:

- Spatial analysis tools are then limited to one CAD tool and may also require the use of specific layer naming conventions that may prove too cumbersome for users;
- In practice, building designers—particularly architects—do not use layering conventions, which undermines any automation attempt; and
- Either the designers do this work for no apparent return, or it is done by construction planners. However, planners do not usually have expertise in CAD use, and our industrial collaborators inform us that it is unlikely that they would be able to acquire such expertise.

Discussions with construction planners during requirements capture, and during system evaluation, suggested that individual definitions of a single space are subjective and often project specific. AreaMan's manual mark-up approach allows individual users to make project-specific decisions when designating individual spaces. In practice, an AreaMan user would manually define the boundaries of an available space using mouse clicks. The tool then calculates the enclosed area, thereby providing a figure for available space for that task execution area. Unlike an automated process, manual mark-up is not dependent on architectural CAD workers having used layer naming conventions. In addition, the user can enter a datum level number, which is then used by VIRCON's visualization tools. Revised plans can be output as DXF files or the spatial data can be uploaded to the VIRCON database.

Functions 7, 8, and 10: Critical Space Analysis with SpaceMan

Once available space has been marked up in AreaMan, tasks can be allocated to spaces using an interface written in MS Project 2000, taking advantage of the "value lists" facility. This interface allows the importation of available spaces via the VIRCON database which can then be viewed alongside the conventional list of tasks derived from the WBS. Tasks can then be assigned to spaces, as shown in the screen-shot presented in Fig. 3, thereby providing the basis for critical space analysis.

SpaceMan is at the heart of our contribution towards providing a solution to the construction space scheduling problem by allowing the easy identification of critical spaces and their relationship to the critical path, and warning construction planners about potential conflicts between them. In addition, it can suggest ways of resolving such conflicts in a process of Space-Time Brokage. A screenshot of the user interface is provided in Fig. 4. The SpaceMan tool takes the following data inputs from the VIRCON database on a weekly basis:

- All scheduled tasks from the WBS (start date, end date, critical path status, etc);
- All available spaces and their task allocations (see above); and
- The amount of space required by each task (from ResourceMan).

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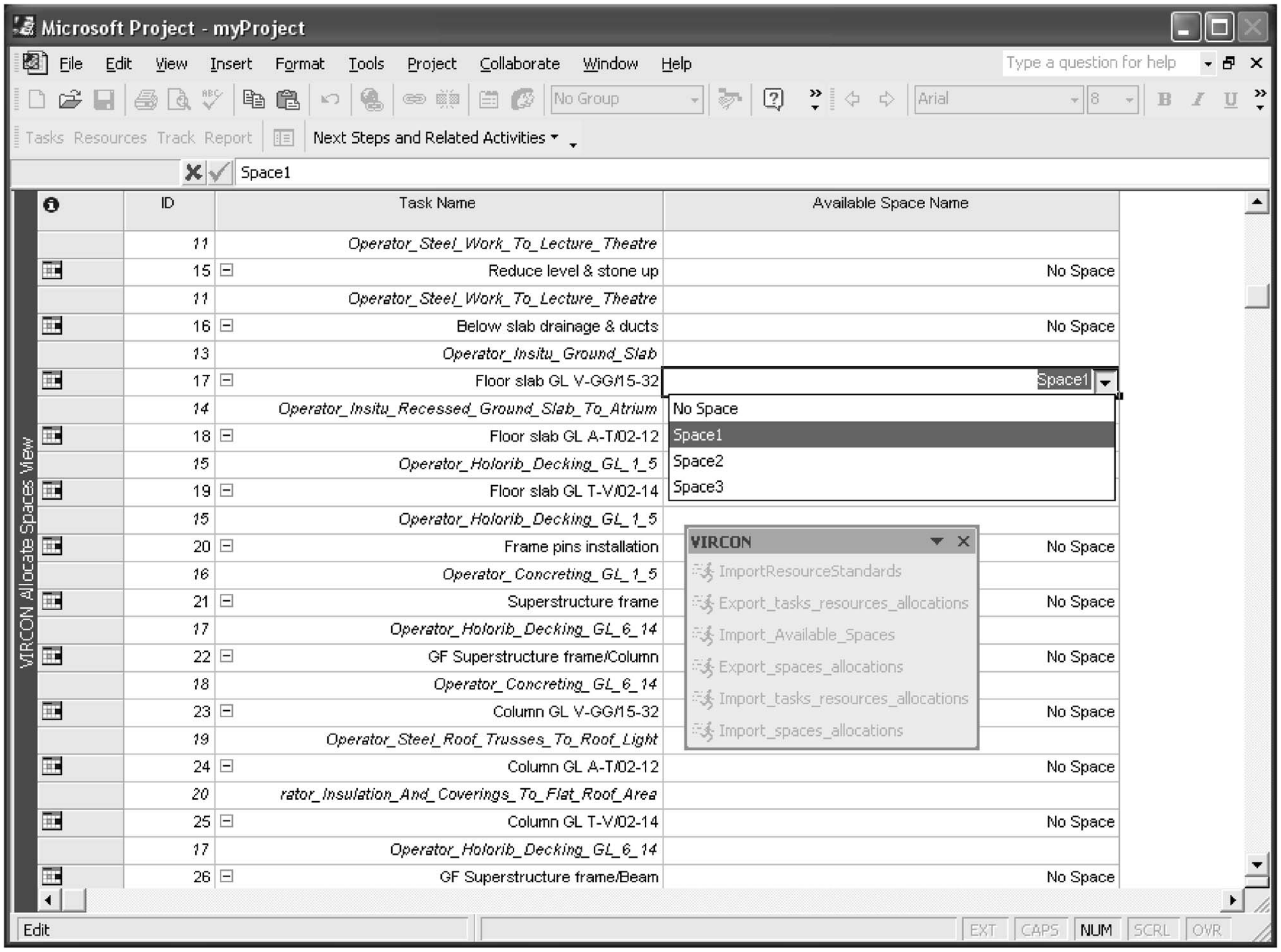

Fig. 3. Screenshot of task assignment in MS Project

It provides the following outputs to inform the scheduling decisions of construction project planners:

- Calculation of the spatial loading for each available space;
- Identification of overloaded available spaces;
- Identification of conflicts between critical path and critical space;
- Suggested schedule revisions in the form of task start and end dates; and
- Data for use by the VIRCON visualization tools.

SpaceMan provides a user interface allowing the easy identification of critical and overloaded spaces ($\mathbf{s}=100$ or $\mathbf{s}>100$), and their relationship to the critical path. The two traffic lights shown in Fig. 4 act as immediate feedback and can be interpreted as follows:

- Left light **green**: currently selected task is NOT on the critical path and there is schedule slack available;
- Left light **red**: currently selected task IS on the critical path;
- Right light **green**: the spatial requirements of tasks allocated to the available space currently selected do not exceed the available space and there is spatial slack available; and
- Right light **red**: the spatial requirements of tasks allocated to the available space currently selected, equal or exceed the available space at some point during that week.

Therefore, a situation where both lights are red indicates that the task execution space currently selected is critical or overloaded and that the currently selected task (which executes in this space) is on the critical path. An obvious initial tactic might be to check the critical status of other tasks executing in this space, to see if they are also on the critical path. Tasks which produce a green left light might be considered good first choices for schedule modification.

The outputs from SpaceMan analysis are the program changes required to both temporally and spatially optimize the project. These take the form of revised task start and end dates, which are uploaded to the VIRCON database where they can be read by both MS Project as a revised schedule and by our visualization applications to provide 3 1/2 D visualizations of critical space and time on the project. Color can be used in these visualizations to indicate levels of spatial loading.

The process of broking space and time considers the balance between *time* (as represented by CPA) and *space* (CSA). In certain project situations space/time conflicts can arise where a choice has to be made between the rescheduling of critical tasks (i.e., those with no schedule slack) and the loading of task execution spaces where $\mathbf{s}$ is at or above unity. A construction planner's decision to revise a project schedule in favor of either time or space priorities might be implemented as a manual or automatic procedure. Discussions with industrial collaborators during VIRCON's requirements capture and evaluation phases indicate a resistance among construction planners to tools that "invisibly" automate decision-making rather than "visibly" supporting it. Therefore the implementation of the Space-Time Broker functionality in SpaceMan operates by flagging up the schedule criticality of a specific task, in much the same way as spatial overloads are

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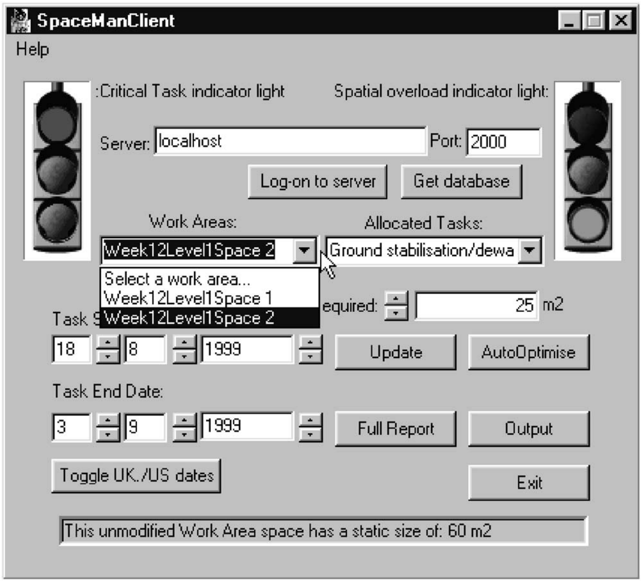

Fig. 4. Screenshot of SpaceMan user interface

indicated. SpaceMan's "two light" system is a simple, nonambiguous approach that informs the user, leaving the necessary course of action up to them.

Spatial overloading may be reduced by the user manually adjusting the tasks allocated to an execution space. However, SpaceMan also allows the application of simple "brute force" algorithms (Bigus and Bigus 2001) to optimize the loading of execution spaces. These algorithms are applied in increasing order of schedule impact. That is to say, SpaceMan attempts to resolve conflicts without changing task durations and resource allocations before trying more drastic solutions. SpaceMan checks after each change to a task (and at each level), jumping out of the process if the spatial conflict has been resolved.

Task durations and resource allocations fixed:

- *Algorithm loop 1*. Move each task's start and end dates within constraints of its earliest start and latest end dates (i.e., within critical path constraints), keeping a constant, relative distance between start and end dates (i.e., task is the same duration). Try all permutations for all tasks allocated to overloaded execution space.
- *Algorithm loop 2*. Move each task's start and end dates within constraints of the execution space's lifespan (i.e., the number of days between the earliest scheduled start date and latest scheduled finish date of all tasks allocated to this execution space), keeping a constant, relative distance between task start and end dates (i.e., task is the same duration). Try all permutations for all tasks allocated to overloaded execution space.
- *Algorithm loop 3*. Move each task's start and end dates without constraint, keeping a constant, relative distance between task start and end dates (i.e., task is the same duration). Try all permutations for all tasks allocated to overloaded execution space.

Task durations and resource allocations variable:

- *Algorithm loop 4*. Move each task's start and end dates within the constraints of its earliest start and latest end dates (i.e., within critical path constraints), with task durations variable. Try all permutations for all tasks allocated to overloaded execution space.
- *Algorithm loop 5*. Move each task's start and end dates within constraints of the execution space's lifespan (i.e., the number of days between the earliest scheduled start date and latest scheduled finish of all tasks allocated to this execution space), with task durations variable. Try all permutations for all tasks allocated to the overloaded execution space.
- *Algorithm loop 6*. Move each task's start and end dates without constraint, with task durations variable. Try all permutations for all tasks allocated to overloaded execution space.

VIRCON Use Case and Relevance to Practitioners

The evaluation reports (Dawood et al. 2003c) of the planners from the collaborating companies encourage us to conclude that the results reported in this paper on the development of critical space analysis are of immediate relevance to practitioners. While experienced planners do take into account spatial issues in planning the temporal sequence of tasks during project execution, they have few—if any—decision support tools to match those readily available for planning the sequence itself. The VIRCON system provides the potential for planners to broker spatial and temporal aspects of the project schedule.

We would envisage the VIRCON system being used in the following manner. It is designed as a strategic construction project planning tool, and so we would expect it to be used initially as part of the precontract development process for the master project schedule, testing the viability of the proposed schedule given the spatial constraints on the project—this part of the process is the basis of our requirements capture, and the speed with which it has to be done in practice is an important part of our rationale for the QUAD approach. Postcontract, the system would be used as part of the schedule development process as appropriate to test its robustness viability of the schedule. We suggest that the system would not be useful for a planning period below 1 week. At the daily level, spatial resources, we believe, are best managed by the supervision on site, rather than from the planning office.

Issues in VIRCON Approach

The main mechanism for applying CSA in the VIRCON system relies on the 2D geometrical information input from the project database, as annotated within AreaMan and PlantMan. Clearly, an evaluation of the potential limitations of this $2D+t$ approach to spatial analysis is necessary, as many authorities advocate a $3D+t$ approach—more commonly known as 4D (e.g., Koo and Fischer 2000; Akinci 2002b; Fischer and Kam 2002). It is the assertion that spatial planning on construction sites is, in essence, a $2D+\mathbf{t}$ problem that allows the QUAD approach to be justified.

Construction project 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? Planners might wish to have the sense of the 3D space and check whether equipment clearances conflict with the roof/upper floor level. They may also wish to consider situations where there are vertical conflicts such as between ceiling level activities (e.g., air conditioning ducting) and floor level activities (e.g., floor tiling). There may also be cases where a completed product overhangs a potentially usable task execution space. Such cases could well benefit from a full 3D spatial analysis.

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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 sterilize the space below it for two reasons. First, 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 that within PlantMan and AreaMan, the task execution space provided by the top of an access platform such as a scaffold is designated as a separate available space, and where access is provided by a mobile platform, it is simply designated as a spatial requirement. Second, 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 equipment movement clearances in the **z** dimension.

The CSA approach builds on the mainstream traditions in construction project planning embodied in critical path analysis, but it is also, we believe, potentially complementary to the newer approaches that are emerging. There are two principal contributions here—*last planner* (Ballard and Howell 1998) and *critical chain* (Goldratt 1997)—more detailed reviews can be found in Winch (2002). For Ballard and Howell, the key to the effective management of site operations 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*. By making only quality assignments, project managers can both reduce costs through increased efficiency and reduce durations by eliminating uncertainty. We propose that the absence of spatial overload as defined above be included as one of the criteria for determining quality assignments. For Goldratt, the *critical chain* is the *longest* human resource constrained path through the network, theorized as a constraint to be elevated. Thus a critical chain looks like a critical path, but it includes human resourcing in the dependencies. We propose that space can also be considered to be a resource in construction project execution alongside human and equipment resources.

Conclusions

The VIRCON research program has taken a distinctive approach to the development of IT tools for construction project planning. A requirements capture phase identified the importance of providing simple, easy-to-use tools that integrated well with the methods already used by construction planners. Other work packages in the research program tackled the issues of site layout and visualization. This paper has reported on the results of the space scheduling related work packages. The VIRCON approach to space scheduling built on earlier work—notably that of Thabet and Beliveau (1994), and Riley and Sanvido (1995)—and the resulting system was compared with more recent research in the area. Three principal contributions were identified:

- The conceptual development of critical space analysis;
- The development of an available space mark-up tool—AreaMan; and
- The development of a critical space analysis and space-time broking tool—SpaceMan.

Other work in the area has assumed that construction planners will have available to them an IFC compatible 4D model before space scheduling can start (e.g., Akinci et al. 2002a). We believe that this is an unlikely scenario, at least within the next 10 years. We have proposed a less technically ambitious approach in IT terms which gives construction project planners most of the functionality of a full 4D approach. Construction space scheduling is, we contend, essentially a 3D problem $(x+y+t)$. However, we do recognize the benefits of the z dimension for program visualization, and so the output from CSA can be—via the VIRCON data base—input into 3 1/2 D visualization tools in both VRML and AutoCAD.

Acknowledgment

This paper was based on research financed by the U.K.'s Engineering and Physical Sciences Research Council (Award No. GR/N00876).

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