Activity-Level Space Scheduling

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ABSTRACT

Activity-level space scheduling involves allocating site space over time to static and dynamic construction resources such as robots. The resulting coarse layouts pertaining to activity-related time intervals serve to coordinate the motion planning of multiple robots. This cannot be done with existing motion planning tools, as computational demands make path-planning for multiple robots in dynamic environments prohibitively expensive. An interactive and graphical decision-support tool, named MovePlan, is presented to assist in space scheduling. Its output layouts can be used to refine individual robot's trajectories using traditional path-planning algorithms.

1   INTRODUCTION

Scheduling involves identifying tasks or activities to accomplish the goals of a project, determining their logical sequencing, and assigning methods and resources so that durations and critical path data can be computed. Associated with activities are resources that require space on site. While space is often omitted in construction management models, it is the sixth resource (besides time, cost, equipment, materials, and labor) to be accounted for in this process. Especially when space is limited, there is a tight interaction between schedule logic, construction method selection, and space availability, so space allocation should be decided upon during schedule construction. Allocating site space required by resources over time as governed by a construction schedule is therefore termed *space scheduling*. It involves identifying individual resource space requirements, determining when and for how long each resource would need space on site, and allocating site space to these resources in different time intervals so that resources are operational and no timing or space conflicts arise.

Space scheduling is typically done at the process level, and then only for critical or expensive resources such as cranes in rigging studies and robots in motion studies. The site space needs for most other resources are generally not planned for. This is in part because it is seemingly not cost-effective to engage in such a detailed study for all resources on site. Taking large numbers of resources into account is often computationally too taxing for existing models.

The view adopted here is that a substantial part of the space allocation task can be performed during early scheduling, possibly before all details about a facility's design configuration or individual resources are known. In fact, the locations, sizes, and shapes of many resources on site throughout construction are only marginally related to the final facility configuration. A fair amount of data needed for space planning can be derived from early design drawings and specifications and serve in making decisions pertaining to the organization of the work, method

selection, and activity sequencing. For example, it may lead to deciding on off-site assembly, on-site prefabrication, or acquiring land for temporary construction laydown.

By not modeling details, computations can be speeded up tremendously. Consequently, tools can be implemented to run on personal computers commonly available on construction sites and thus be made widely available. In addition, the reduced complexity in modeling individual resources makes it possible to simultaneously plan for many resources that move about the site.

As soon as a schedule of production activities is constructed, one can plan—at the desired level of detail—the mobilization, movement, and demobilization of major equipment; the delivery and laydown of materials; and the location and size of other storage or fabrication areas. When a total space histogram is constructed, it can be used to identify high demand for site space. Coarse or detailed layouts for larger or smaller time intervals can then be constructed. If regularly updated, the space schedule can serve as a layout plan to organize site work, monitor construction progress, and control materials and equipment. Alternatively, it can be further refined using path-planning procedures to route individual robots.

2 RELATED WORK

Existing tools for modeling the use of space required for construction operations fall into two categories: layout tools and construction sequencing tools.

2.1 Layout Tools

Layout tools are used for positioning facilities, such as temporary warehouses, trailers, and laydown areas, that will remain in place for a substantial time period relative to the duration of construction. They are used for planning a project overall. Sketches, marked-up blueprints, and cut-out templates are commonly used for constructing site layouts (Henderson 1976). Although computer-based tools exist (Rad 1982, Hamiani 1988, Tommelein 1989, Tommelein et al. 1991, 1992b 1992c), they are rarely used in the field.

An overall site arrangement that spans the entire duration of construction is typically drawn at the beginning of construction. This layout is seldom updated as construction progresses because collecting spatial information on site is tedious. Moreover, the traditional layout tools are not linked to the activity schedule, so using current schedule information for updating the layout not as straightforward as it could be. To our knowledge, there are no layout tools (besides the MovePlan model presented here) that dynamically link layout information to an activity schedule and vice versa The layout thus becomes outdated as site conditions change and deviate from what was planned.

2.2 Construction Sequencing Tools

Construction sequencing tools are used to study the movement of a specific piece of equipment during material handling (Bechtel 1988, Zabilski and Hall 1989, Morad et al. 1992). They are used for planning an individual process; specifically, one in which several resources may interfere with one another. Computer-based tools are most common for these studies, because the calculations required for checking interference are highly repetitive. Such tools often require dedicated workstations as they are computationally intensive and output sophisticated graphics.

While most useful for assessing the constructibility of a project, these detailed studies can only be undertaken when data is available about the exact geometry of the involved resources and facility. In addition, data entry is time-consuming and workstation use expensive. So, construction sequencing studies are done only for selected processes, when all facility design details are known, i.e., not during preliminary planning, nor for the entire duration of a project.

Construction sequencing is studied when critical or expensive resources are involved, such as cranes in rigging studies and robots in motion studies. The site space needs for most other resources are generally not planned for, in part because it is not cost-effective to engage in such detailed studies for all resources on site, in part because it is computationally too demanding.

A difficult problem in studying the motion of a dynamic resource is determining its optimal path when obstacles are present (Latombe 1988). This problem is even more complicated when obstacles themselves move, or when multiple dynamic resources are present. Most models therefore limit themselves to single-resource path planning. This limitation oversimplifies the dynamic environment that is encountered on construction sites. A new model is therefore proposed to enable planning path planning and construction space scheduling at the project level.

3 SPACE SCHEDULING ISSUES

The space scheduling task differs from other resource allocation and scheduling tasks in its degree of complexity. Space scheduling involves the non-scalar variable "space," which is not additive, like cost or time or other resources. Indeed satisfying spatial constraints requires not only checking total area availability; it also requires checking fit and location. In addition, space planning over time requires checking path interference.

The key source of information regarding resources and the timing of their presence on site is the activity schedule. The main schedule used in construction shows the relation between production activities. Other schedules are complementary. For example, procurement schedules reflect resource delivery activities that necessarily precede production activities. The production activity schedule may serve in a first iteration of space scheduling, but its data is generally incomplete. Procurement activities need to be added to the network to reflect resource space need before and after production activity starts and finishes. Activities may also need to be split up to show resource fluctuations over their duration. Such additional refinements will enable the space schedule to more realistically model the site's layout over time.

Resources are called *operational* for the time period over which they are involved in production activities. Upon activity completion, they may remain on site, awaiting use in the next production activity. By definition, these resources are then called *non-operational*. During this period in-between production activities, they could remain stationary and idle or be relocated.

For each time interval, the position of each (dynamic) resource must be decided. A single *average position* is computed for each resource in each layout and corresponding time interval. A static resource remains in place for the entire duration of the layout interval, so thát position is well-defined. In contrast, a dynamic resource's position is defined to be halfway along its path from start to finish, assuming it travels at a uniform speed along a straight line over the time interval to which the layout applies.

Furthermore, a resource's shape and dimensions must be specified, possibly as a function of time. How shape and dimensions used in representation relate to the resource's actual shape and

dimensions is a research issue on its own. A more detailed description of how they might affect space scheduling is given in (Tommelein et al. 1992a).

4   CONCEPTUAL DESCRIPTION OF MOVEPLAN

The MovePlan decision-support tool was developed to address activity-level space scheduling. MovePlan takes as input the logical sequencing and durations of activities, and their associated resources and corresponding space needs. MovePlan computes critical path data and resource histograms, not only for the traditional one-dimensional variables but also for two-dimensional space. MovePlan then enables its users to plan the location and movement of resources on site for discrete time intervals. It supports users by identifying which resources are on site for a given time period, but more importantly, the program keeps track of resources that have been positioned in time-overlapping layouts. Its underlying constraint network and constraint propagation mechanisms enforce that only consistent layouts be generated, i.e., a resource can only be in one location at any one time). Thus the system relieves users from this painful cognitive task.

MovePlan's modeling assumptions are conservative, but in most cases not restrictive. They are:
- space is continuous and two-dimensional
- the project duration can be sliced in time intervals that are discrete and of any length
- for each interval, resources are shown at their average position
- the project site, building, and all resources are rectangular in shape
- resources have fixed dimensions for the duration of the activity they are involved in
- resources can be associated with one or several activities
- resources are on site for their activities' early-start to early-finish duration
- schedule and layout construction are sequential. The schedule cannot be changed when the first layout is generated.

Entering input data is made easy through MovePlan's interactive user interface. The data required includes:
- site dimensions
- project dimensions and position
- description of activities and their durations
- logical relationships between activities
- resources needed for each activity and resource dimensions

MovePlan output includes displays of interesting pieces of data that assist the user in decision-making, such as:
- a time-scaled bar-chart schedule
- individual resource histograms
- a space histogram
- interactive graphical displays to enable users to select time frames, position resources, and thus construct or improve layouts over time.

MovePlan has a MacDraw-like interface and an underlying consistency maintenance system. For a user-selected time interval, MovePlan displays the available site space with the building footprint in a view with scaled site dimensions. The program collects the resources that are on site for the selected interval, and provides templates representing each resource's scaled space need. MovePlan automatically displays resources that were positioned in a time-overlapping

layout at their previous position. A consistency check is performed before displaying resources: previously positioned resources whose position in the current layout can be changed by the user are tagged, the others are locked at their position. All resources are made mousable to display their name, position, and dimensions. When the current layout is changed, the resource positions in the space schedule are updated and stored. MovePlan 1.0 is implemented in the object-oriented Macintosh™ Common Lisp language, MCL 2.0.

5 EXAMPLE

An example will illustrate one way of using MovePlan for space scheduling. Consider the following scenario of planning the travel of a robot pipelayer, given that other resources are on site and may or may not be operational. The network shown in Figure 1 describes the activities pertaining to the construction of a drainage system and foundation walls surrounding a building. Construction is staged, starting with the East (E) and South (S) foundation walls, followed by the North (N) and West (W) foundation walls. In parallel with the "concrete activities" (i.e., placing formwork, rebar, and concrete) are pipelaying activities (i.e., placing pipe, backfilling the trench) along the S and N walls. The pipelaying activities proceed in a clockwise manner starting at the SE corner of the building and finishing at the NE corner.

A single pipelayer (resource R13) places pipes along the S foundation wall (activity 2) followed by those along the N foundation wall (activity 8). After finishing the first activity, the pipelayer needs to be moved from the S side of the building to the N side before starting the second activity. Pipelaying is followed by a font-end loader (resource R7) backfilling the trenches along the S and N foundation walls (activities 5 and 11 respectively).
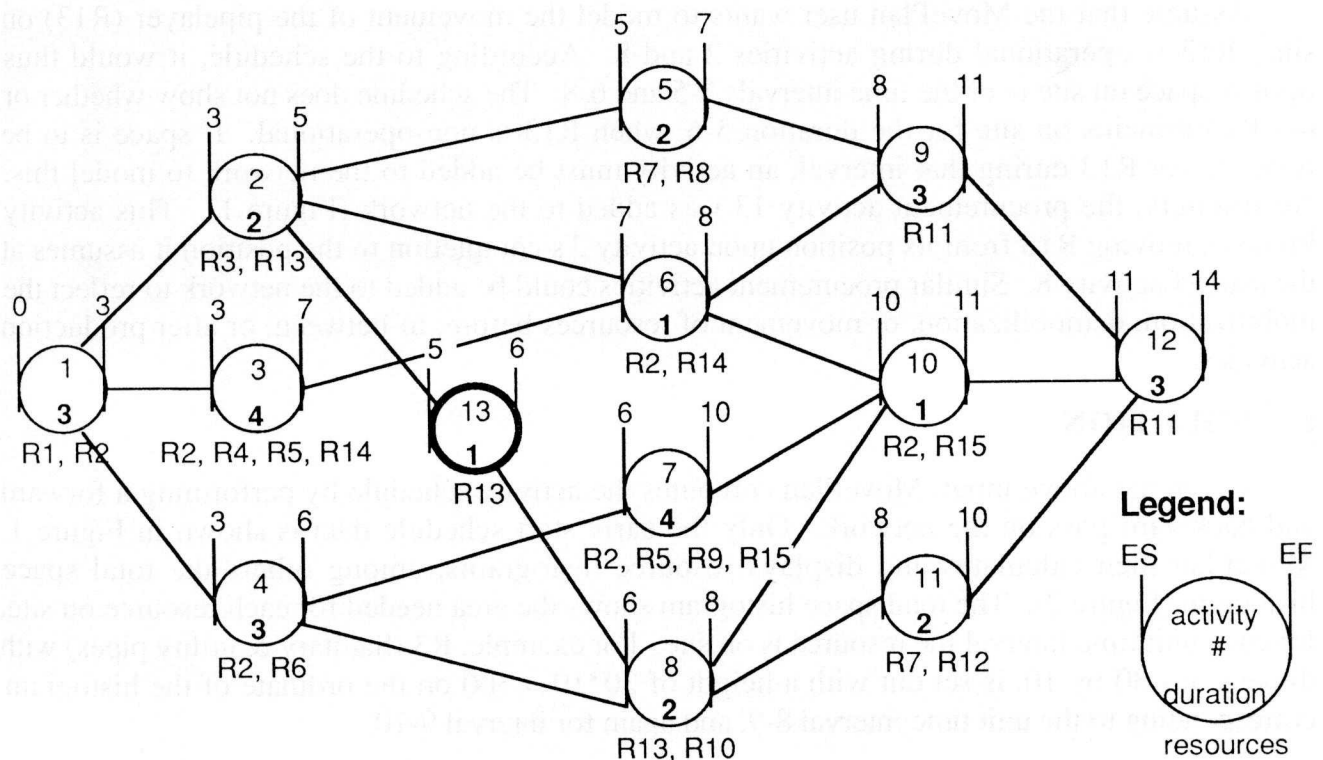

Figure 1: Example project network showing activities and associated resources.

Input to MovePlan includes data regarding the construction site, the activity network, resources and their dimensions. The construction site area is rectangular with dimensions 125 by 110 (in unit measure, such as feet or meters). The building is a 70 by 50 rectangle; its upper left corner is located at 45 E and 35 S of the NW corner of the site. The construction network is specified, including logical relationships between activities, activity durations, and the resources associated with each activity (Figure 1). In addition, the dimensions of individual resources and activity descriptions are entered into MovePlan (Table 1).

Activity Description	Resource Description	Resource Dimensions
1. Formwork found. wall S&E	R1: Formwork lumber	20 x 12
2. Pipelaying S	R2: Crane	12 x 7
3. Form rebar S&E	R3: Sanitary & utility pipes	30 x 10
4. Formwork found. wall N&W	R4: Rebar #4 & #5	20 x 12
5. Backfilling S	R5: Rebar shop	15 x 10
6. Place rebar S&E	R6: Formwork lumber	20 x 12
7. Form rebar N&W	R7: Front-end loader	10 x 14
8. Pipelaying N	R8: Backfill material	20 x 30
9. Place Concrete S&E	R9: Rebar #4 & #6	20 x 12
10. Place rebar N&W	R10: Sanitary & utility pipes	30 x 10
11. Backfilling N	R11: Concrete pump	15 x 20
12. Place concrete N&W	R12: Backfill material	20 x 30
13. Move pipelayer	R13: Pipelayer	14 x 10
	R14: Formed rebar #4 & #5	30 x 30
	R15: Formed rebar #4 & #6	30 x 30

Table 1: Example project network's activities, resources, and resource dimensions.

Assume that the MovePlan user wants to model the movement of the pipelayer (R13) on site. R13 is operational during activities 2 and 8. According to the schedule, it would thus occupy space on site over the time intervals 3-5 and 6-8. The schedule does not show whether or not R13 remains on site for the duration 5-6, when R13 is non-operational. If space is to be reserved for R13 during that interval, an activity must be added to the network to model this. Accordingly, the procurement activity 13 was added to the network (Figure 1). This activity involves moving R13 from its position upon activity 2's completion to the position it assumes at the start of activity 8. Similar procurement activities could be added to the network to reflect the mobilization, demobilization, or movement of resources before, in-between, or after production activities.

6 SOLUTION

Given the above input, MovePlan computes the activity schedule by performing a forward and backward pass on the network. Only the early start schedule data is shown in Figure 1. MovePlan then calculates and displays resource histograms, among others the total space histogram (Figure 2). The total space histogram shows the area needed for each resource on site, for each unit time interval the resource is on site. For example, R3 (Sanitary & utility pipes) with dimensions 30 by 10, is set out with a height of 30*10 = 300 on the ordinate of the histogram corresponding to the unit time interval 8-9, and again for interval 9-10.

Guided by the total space histogram, the MovePlan user identifies the time period with greatest site space demand, that is, the time period most likely to site congestion. This period 6-7 corresponds to the histogram's peak. To ascertain site space availability can meet demand, the user creates a layout for this interval (Figure 3.b). The resources R2, R4, R5, R8, R14, R15, R10, R9 all represent laydown areas, which tend to remain in a single position for the duration they are on site. R7 and R13 are the only dynamic resources in this interval.

The arrival of these dynamic resources should not hold up activity starts. Therefore, the user must (1) determine the resources' position at the end of the production activity in which they were previously involved, and (2) see if the resources can be moved to their new location in the time interval in-between their previous and new production activities.

MovePlan's individual resource histograms of R13 and R7 respectively (not shown) assist the user in identifying all production activities in which these resources are involved. For example, R13 was operational in activity 2 for duration 3-5. The user thus decides to determine R13's position in that interval, and draws R13 at its time-average location along the S wall of the building while traveling from the SE to the SW corner of the building (the direction of motion is indicated by the arrow in Figure 3.a; arrows are not part of MovePlan's display). Since R13 is assumed to travel at a uniform speed during the activity duration, the time-average position falls half-way in between the building's corner points.

MovePlan shows the other resources on site for interval 3-5 to the user. If these have positions in a time-overlapping layout, they are drawn in their previous position; otherwise, MovePlan provides templates for the user to manipulate until a satisfactory position is found. The resulting layouts 3-5 and 6-7 might meet the user's need for layout detail. However, if more detail is needed, e.g., to plan the motion of resources, the time intervals could be refined further.

The motion of R13 from its ending position in activity 2 to its begin position in activity 8 can be planned by refining time interval 5-6. That is, the interval 5-6 can be divided up into any number of smaller intervals. If one interval is chosen (5-6 itself) R13 would assume an average position half-way along the SW and the NW corner of the building. In contrast, the user may choose four equal-length intervals and have MovePlan create layouts for intervals 5-5.25, 5.25-5.50, 5.50-5.75, and 5.75-6. Again, resources from time-overlapping layouts are shown by MovePlan in their previous positions. Other resources are to be positioned by the user. Thus, the motion of R13 as well as that of R7 is discretized by one of four average positions (Figures 3.c through 3.f).

7 DISCUSSION

MovePlan's outputs enable users to extract important management knowledge, such as spaces that are occupied by different resources over time. For example, the area allotted to R3 in 3-5 is later occupied by R8. The program ignores many process-planning details, such as the time it takes to rotate a resource. It shows resources in their average position, which may at first be counter-intuitive. That is, display of the actual path followed during a layout's time interval might add to the clarity of the representation, and the program should be able to infer intermediate positions of a resource, when given its travel speed and start and end points. Average positions are useful however, because they can be input to traditional path planning systems in order to be refined.
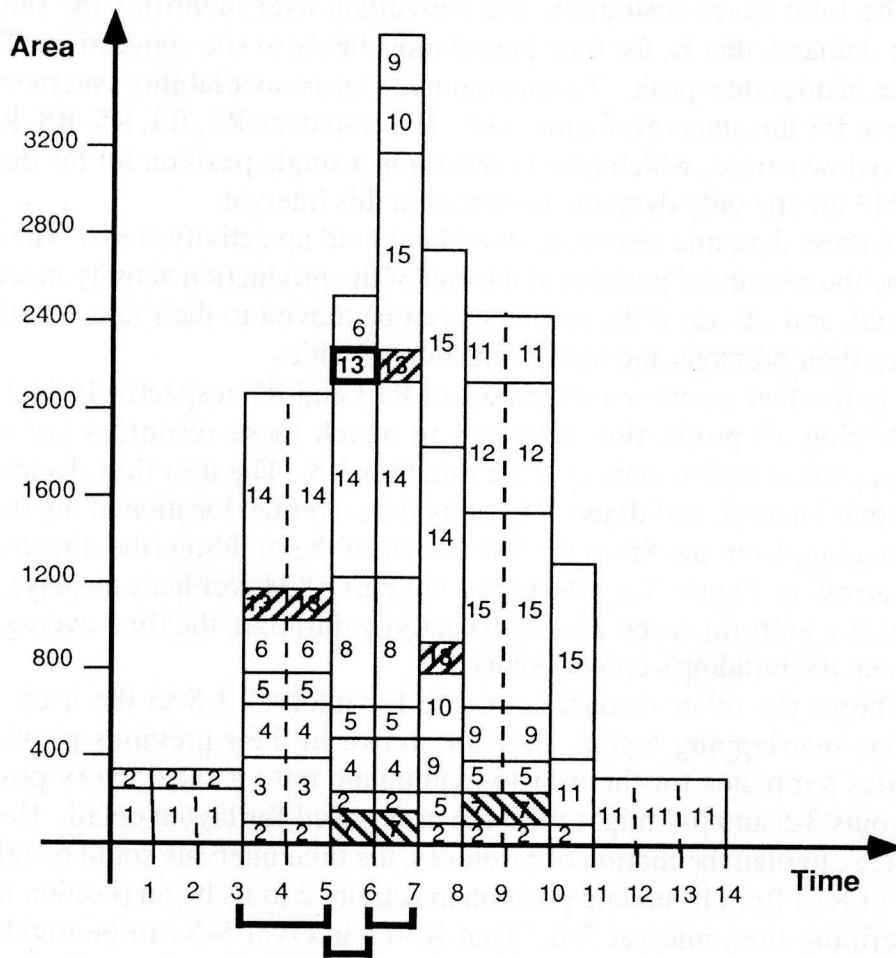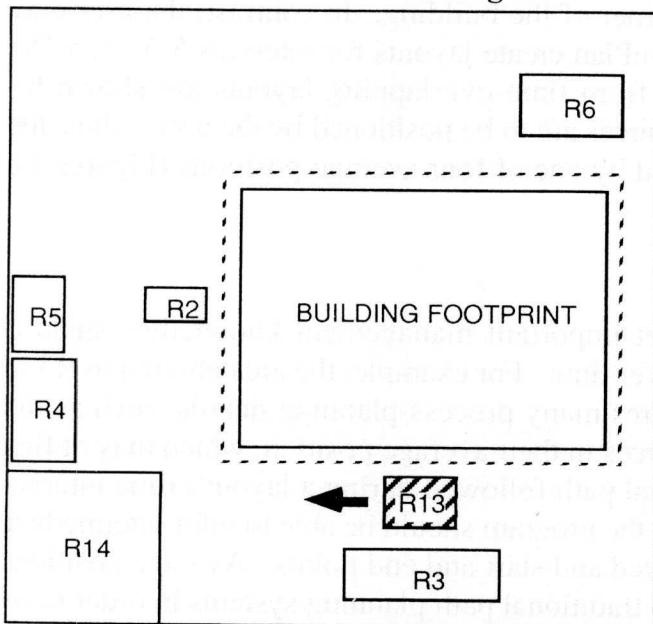
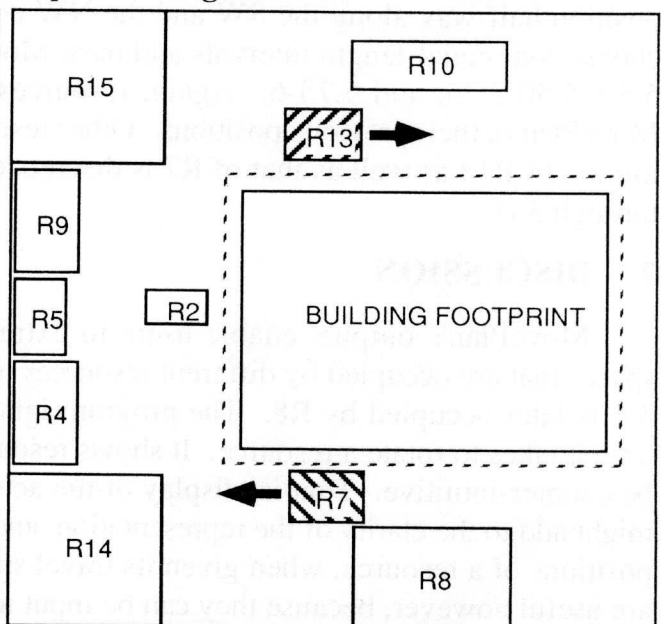**Figure 2: Total Space Histogram**

Figure 3.a: Layout 3-5

Figure 3.b: Layout 6-7

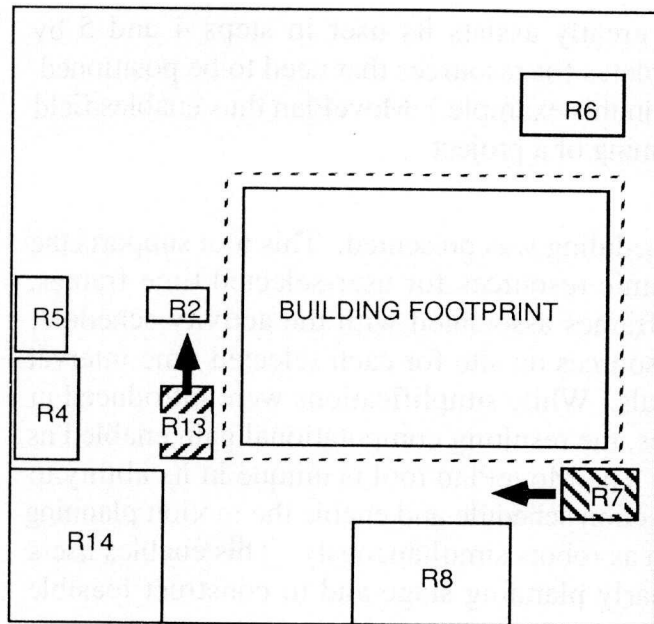Arrows show the direction of motion; the dashed line shows the edge of the building excavation.
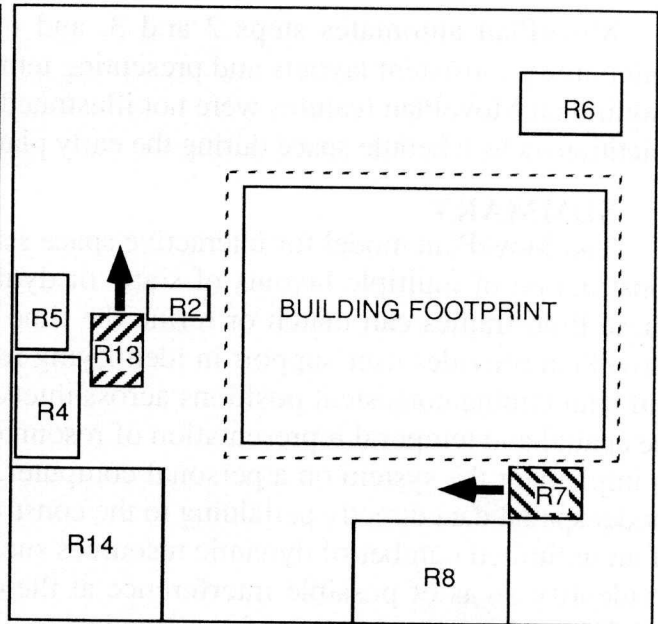
Figure 3.c: Layout 5-5.25

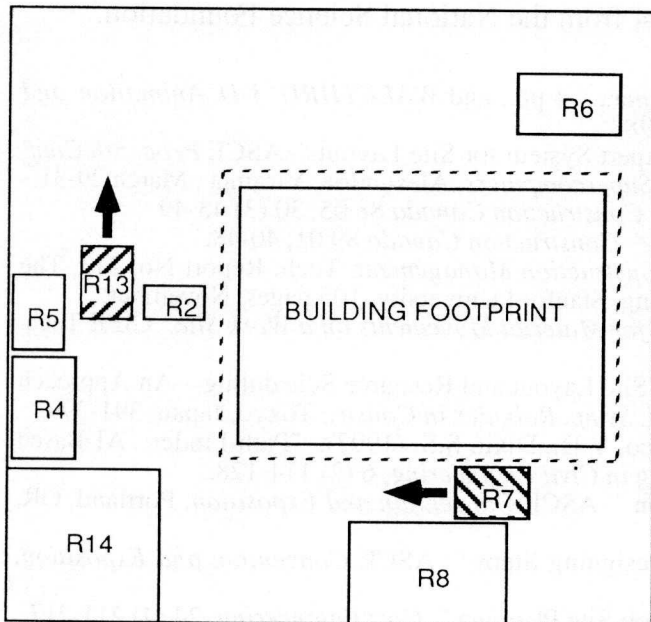**Figure 3.d: Layout 5.25-5.50**
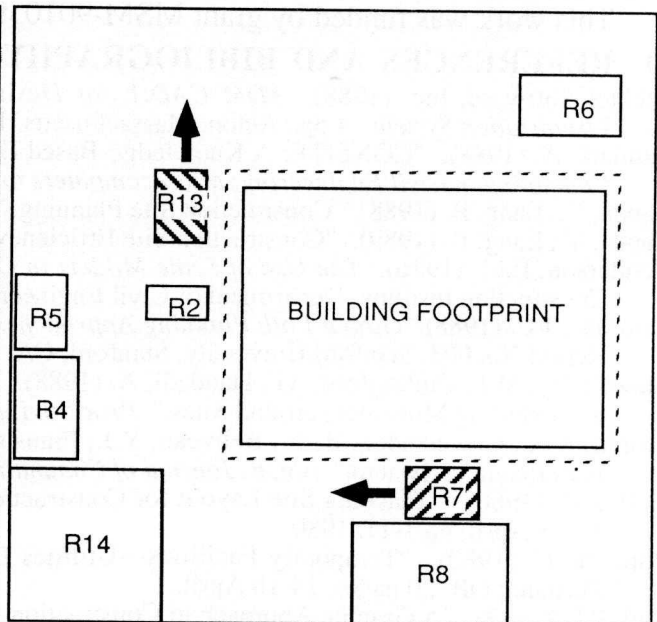

Figure 3.e: Layout 5.50-5.75

Figure 3.f: Layout 5.75-6

It is at the user's discretion as to how much detail is shown in the layout and in the time intervals. The user can define any number of activities, any number of resources of any dimension associated with activities, and any time interval to create a layout. In the extreme, time intervals could be very short. A playback of all layouts in sequence would then simulate the site's change over time like a motion picture.

The following process is repeated until a satisfactory sequence of layouts is obtained:

1. Enter project data.
2. Compute the schedule.
3. Generate total space histogram.
4. Select time frame for a layout.
5. Construct the layout.
6. Repeat steps 4 and 5.

MovePlan automates steps 2 and 3, and it greatly assists its user in steps 4 and 5 by maintaining consistent layouts and presenting templates for resources that need to be positioned. (Additional MovePlan features were not illustrated in this example.) MovePlan thus enables field practitioners to schedule space during the early planning of a project.

8 SUMMARY

The MovePlan model for interactive space scheduling was presented. This tool supports the construction of multiple layouts of static or dynamic resources for user-selected time frames. These time frames can match or refine the time frames associated with the activity schedule. MovePlan provides user support in identifying resources on site for each selected time interval and maintaining consistent positions across intervals. While simplifications were introduced in the spatial and temporal representation of resources, the resulting computational gain enabled us to implement the system on a personal computer. The MovePlan tool is unique in its ability to model spatial data directly pertaining to the construction schedule and enable the motion planning of an unlimited number of dynamic resources such as robots simultaneously. This enables users to identify areas of possible interference at the early planning stage and to construct feasible layouts for the entire duration of construction.

9 ACKNOWLEDGEMENTS

10 REFERENCES AND BIBLIOGRAPHY

Bechtel Software, Inc. (1988). *3DM CAD/E for Designers.* 4 pp., and *WALKTHRU 3-D Animation and Visualization System.* 4 pp., Acton, Massachusetts, 1988

Hamiani, A. (1988). "CONSITE: A Knowledge-Based Expert System for Site Layout." ASCE *Proc. 5th Conf. Computing in Civil Engineering: Microcomputers to Supercomputers*, Alexandria, Virginia , March 29-31.

Handa, V., Lang, B. (1988). "Construction Site Planning." *Construction Canada* 88 05, 30 (3) 43-49.

Handa, V., Lang, B. (1989). "Construction Site Efficiency." *Construction Canada* 89 01, 40-48.

Henderson, E.M. (1976). *The Use of Scale Models in Construction Management.* Tech. Report No. 213, The Construction Institute, Department of Civil Engineering, Stanford University, 105 pages, November.

Latombe, J.C. (1988). *Global Path Planning Approaches for Material Movements on a Work Site.* CIFE Tech. Report No. 003, Stanford University, Stanford, CA.

Mawdesley, M.J., Cullingford, G., Haddadi, A. (1988). "Site Layout and Resource Scheduling—An Approach to Modelling Movement around Sites." *Proc.5th Intl. Symp. Robotics in Constr.*, Tokyo, Japan, 391-399.

Morad, A.A., Cleveland, A.B. Jr., Beliveau, Y.J., Fransisco, V.D., Dixit, S.S. (1992). "Path-Finder: AI-Based Path Planning System." *ASCE, Journal of Computing in Civil Engineering*, 6 (2) 114-128.

Neil, J.M. (1980). "Teaching Site Layout for Construction." ASCE *Convention and Exposition*, Portland, OR, 14-18 April, pp.1-11, 1980

Popescu, C. (1980). "Temporary Facilities—Utilities Designing Steps." ASCE *Convention and Exposition*, Portland, OR, 20 pages, 14-18 April.

Rad, P.F. (1982). "A Graphic Approach to Construction Job-Site Planning." *Cost Engineering,* 24 (4) 211-217.

Tommelein, I. D., Castillo, J. G., Zouein, P.P. (1992a). "Space-Time Characterization for Resource Management on Construction Sites." ASCE, *8th Conference on Computing in Civil Engineering*, June 7-9, Dallas, TX.

Tommelein, I.D., Levitt, R.E., Hayes-Roth, B. (1992b). "The SightPlan Model for Site Layout." *ASCE, Journal of Construction Engineering and Management*, in press.

Tommelein, I.D., Levitt, R.E., Hayes-Roth, B. (1992c). "Site Layout Modeling: How Can Artificial Intelligence Help?" *ASCE, Journal of Construction Engineering and Management*, 118 (3), September 1992, in press.

Tommelein, I.D. (1991). "Site layout: Where should it go?" in *Preparing for Constr. in the 21st Century,* ASCE Proc. Constr. Congr. 91, Cambridge, Mass., 632-637.

Tommelein, I.D., Levitt, R.E., Hayes-Roth, B., Confrey, T. (1991). "SightPlan Experiments: Alternate Strategies for Site Layout Design." *ASCE, Journal of Computing in Civil Engineering*, 5 (1) 42-63.

Zabilski, R.J., Hall, H.E. (1989). "Presented in 3-D." ASCE, *Civil Engineering*, 48-50, June.

Zouein, P. P., Tommelein, I.D. (1992). "MovePlan: Allocating Space During Scheduling." *Proc. CIB 92 World Building Congress*, National Research Council Ottawa, Canada, 18-22 May.