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# Space Scheduling for Construction Progress Planning and Control

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**Abstract**

Space scheduling pertains to allocating work space to resources associated with activities in a schedule as it changes over time. This is an important aspect of materials management in dynamic environments in which many pieces of equipment, crews, and possibly robots move about, as congestion and interference would seriously hamper production. Advance space scheduling is then warranted to reduce the need for real-time sensing and adjusting. Reactive space scheduling may be needed when problems have arisen and must be alleviated. In any case, space-schedule data must be made available in a timely fashion to all parties who need it. The MovePlan model for dynamic layout planning is described to illustrate the overall significance of space scheduling to construction progress planning. MovePlan uses a two-dimensional representation of space to keep the computational costs associated with space-time calculations low. Accordingly, the model does not require a powerful workstation, but runs on a laptop computer—and is expected to run on a palmtop—that could easily be taken out into the field. MovePlan has been loosely integrated with a space-schedule conflict resolver, named ConRes, which delays activities or changes their resource needs to lower the demand for space in so-called problematic time intervals. Issues pertaining to data collection for space scheduling, scheduling progress control, and data dissemination are discussed. A futuristic scenario is presented to illustrate the use of palmtop computing for space scheduling on site.

## 1. INTRODUCTION

In the last decade, microcomputer development has progressed tremendously and computer hardware costs have plummeted. Personal computing devices are now ubiquitous in construction home offices and on construction sites.

Several site materials management programs, including those described in this paper, are currently being developed to run on networked laptop computers. While such programs exhibit many useful features, they are limited in use due to the hardware on which they run. To make on-site computing become reality, wireless communication is a necessity and robust hardware must be developed to resist the harsh site conditions (e.g., large temperature gradients, dust, impact, and variable weather) under which construction is performed.

automatically-generated solution. The development of interactive, heuristic decision support tools to aid them with dynamic layout planning and space scheduling is therefore advocated.

It is generally the case that construction schedules are too abstract (esp. executive-level milestone- and work package-, but even task-level schedules), i.e., they do not represent enough detail to model the need for, use, and availability of space. Only overall site arrangements can be studied early on in the planning process. Not enough decisions have been made at that time to allow for detailed space schedule development. Sufficient detail at the process level must be available (e.g., during daily crew-level planning) to warrant detailed space scheduling. Accordingly, it is at the process level that spatial and temporal data must be collected and used to enable individual workers and crews to organize their work on site and to gauge their progress. The term **progress planning** is used to denote this.

## 3. SPATIAL AND TEMPORAL DATA

### 3.1. Data Collection

The collection of large amounts of real-time field data has been made possible by the development of new tools such as laser-controlled and bar-coding systems. Laser-controlled systems assist in positioning the blades of grading equipment. This benefits individual equipment operation. Bar-coding of construction components (e.g., Bell and McCullouch 1988, Rasdorf and Herbert 1990a, 1990b) facilitates component identification and inventory status tracking. This benefits site management (performing tasks such as purchasing, inventory control, and accounting), but there is little mention in the literature as to how these tools and the collected data can be used to improve crew-level operations and construction planning overall.

Data needed at the crew level should provide information to individual workers or superintendents when they are planning or executing work. It should provide answers to questions such as:

*Where is the formwork?*
*Have the windows already been delivered? When will they arrive?*
*What is the nearest supply of two-by-fours?*
*Could I use the sheet rock that is over there? What will it be used for?*
*What is the best way to get to the management trailer?*
*Could I use that forklift to move the brick pallets closer to my work area?*
*Will that area be available tomorrow to set up a fabrication shop?*

Clearly, much of the data needed to answer these questions changes over time. Materials may be brought to the site by one person, who needs to inform others of their arrival. Supplies get replenished during the course of the day, so workers who are waiting for them must be readily informed of their availability. The nearest supply depends on where a worker is standing and varies as work progresses and that worker moves around. A material may appear to be available to one worker, but may have been designated for sole use by others. Congested and dangerous work areas must be circumvented if possible. Utility equipment gets used opportunistically, it does not get scheduled; what appears to be idle at one time, may be tied up later. Crews need to communicate their plans to avoid future competition for resources or interference. Not only is it necessary to make

The further decrease in size from laptop to palmtop computers, together with the standardization of wireless communication protocols, will change site management techniques. Their combination is likely to have a major impact on field productivity. In anticipation of the advent of such low-cost devices, the data needs of field personnel should be re-engineered to improve data collection, planning and scheduling, control, as well as data dissemination. Specifically, the focus of attention should be on characterizing construction resources in terms of their handling, including the space they require and the timing of their presence on site (Tommelein et al. 92). Research must investigate new methods to effectively model resources tied to site space needs and scheduled time to augment existing materials management systems (Bell et al. 87, Bell and Stukhart 86, 87; Lundberg and Beliveau 89).

## 2. TERMINOLOGY

When space is limited, tradeoffs between activity sequencing, timing, method selection, resource allocation, and space allocation are necessary to plan executable schedules and feasible layouts. When space is abundant, similar tradeoffs exists as, for example, travel distance and reach of selected hoisting equipment affect materials handling efficiency. The resource *space* as a variable in the scheduling process has not been modeled with much detail, possibly because of the complexity of the interaction between spatial and temporal aspects of resource needs and availability. To define the possible degree of interaction, two terms are used:

**Dynamic layout planning** (Tommelein and Zouein 93) refers to the unidirectional interaction between the scheduling and space allocation tasks. After a sequence of activities has been defined and resources with their dimensions have been associated with each activity, the schedule is considered to be final. It serves as input to the space allocation task.

Layouts can then be constructed for selected time intervals, each layout using the resources that are scheduled to be present during the interval it spans. It may be that no feasible layout can be constructed to accommodate all resources in each interval. In that case, the dynamic layout planning problem cannot be solved, possibly—but not necessarily—because the schedule was frozen.

**Space scheduling** (Zouein and Tommelein 93) refers to the bidirectional interaction between the scheduling and space allocation tasks. (Dynamic layout planning is thus a subtask of space scheduling.) A sequence of activities must be defined, resources with their dimensions associated with each activity, and space on site must be identified for each resource. Schedule construction is performed concurrently with layout construction. When layouts are found to be infeasible, schedule changes might alter the problem so that it becomes solvable. For example, activities can be delayed or have their resource use level changed to shorten or lengthen in duration.

Dynamic layout planning and space scheduling both are limited resource allocation problems involving the inherently two- (actually three-) dimensional variable *space* in addition to the scalar variables equipment, labor, materials, time, and possibly money. In general, limited resource allocation problems can be solved using heuristic methods only; no optimization techniques exist. This is one reason for which people who use such models conduct what-if analyses and experiment with alternate problem formulations, before accepting an spatial data available in a timely fashion to all people who need it; logging data as it changes over time must be done by all (or at least many) people on site as it is beyond the scope of what a single individual can do.

## 3.2. Planning and Scheduling

Few tools, beyond databases and traditional CPM programs, are currently available to aid with materials management as a true construction scheduling task. Construction materials come in great variety and arrive to the site under uncertain conditions. This poses challenges to management, beyond those of materials management in a steady-state manufacturing environment. The space resources require on site, their bulkiness, etc. may be a major hindrance in executing work according to plan. Managing materials accounts for a substantial part of construction cost, however, and research should investigate which models lend themselves to use on site.

## 3.3. Progress Control

Spatial data is particularly important at the process level. This is the level at which interferences can be prevented, excessive travel times identified, and appropriate material handling means selected. Three-dimensional CAD tools have been developed in recent years for checking interferences during the on-site movement and placement of exceptional loads. Little is formalized about the handling of most other materials on site, which are in the majority. The process level is also the level at which work progress can best be measured and hurdles overcome. It is therefore advocated that spatial data be included in control systems, which all too often limit themselves to modeling only durations and costs. An augmentation of simulation tools with spatial abstraction mechanisms might fill the need for tools to study the space-time-cost trade-off.

## 3.4. Data Dissemination

Materials data should be made available to all on site who need it. As different people have different data needs, appropriate abstraction mechanisms must be developed. Discussing these is beyond the scope of this paper. One issue worthwhile raising is that everyone on site will need a communication device to enter new and query existing data, but tight controls must be kept to guarantee data consistency and correctness. Wireless palmtop computers equipped with intelligent interfaces are expected to be able to meet those needs.

# 4. ENVISIONED FIELD IMPLEMENTATION

## 4.1. Software Needs

Few existing computer-based scheduling programs represent the resource *space* as an explicit variable. New software is therefore being developed to keep track of space schedules and to answer questions such as those mentioned in section 3. Our work includes three models, which address the space scheduling task with increasing degrees of complexity.

### 4.1.1. MovePlan

Laying out temporary facilities on site all too often means to manually mark up a site arrangement drawing, showing different overlapping laydown areas that will be present for consecutive time frames. This results in a complicated drawing that can be interpreted only by the one who made it, and that by no means lends itself to updating as construction progresses. Its use for task coordination and materials management is thus very limited.

The MovePlan interactive dynamic layout planning tool (Tommelein and Zouein 1993) exactly addresses this problem. MovePlan needs as input a schedule of activities annotated with their resources, the two-dimensional and rectangular space each resource will need on site, data describing the permanent resources on site, and the site's boundaries. It enables users to create layouts for time intervals of any length, related to parts of the early-start project schedule.

The tool aids in solving this dynamic layout planning task by providing templates representing the resources that are on site for the selected interval, and a worksheet in which those templates can be moved around. The worksheet is scaled to the site boundaries and shows where permanent and previously-positioned resources are. When time-overlapping layouts are created, MovePlan maintains consistency among them. A resource that has been assigned to a position in one layout, is shown in the same position in any layout that overlaps in time with the first one and that includes the resource. MovePlan freezes the schedule as soon as the first layout has been saved. A play-back of the dynamic layout sequence shows how the site space use changes over time. The tool thus provides decision support to field engineers who arrange resources on construction sites and coordinate subcontractor or crew activities.

The MovePlan user may find that the layout for a chosen time frame is unsatisfactory (e.g., because it is too congested or no space is available to locate a critical resource). In this case, it may be possible to delay the arrival of some resources in order to free up space for others, or to assign different resources to activities. Pertinent data must then communicated to a conflict resolver that makes the appropriate schedule changes. Schedule changes are subsequently returned to MovePlan for the user to continue with the layout task.

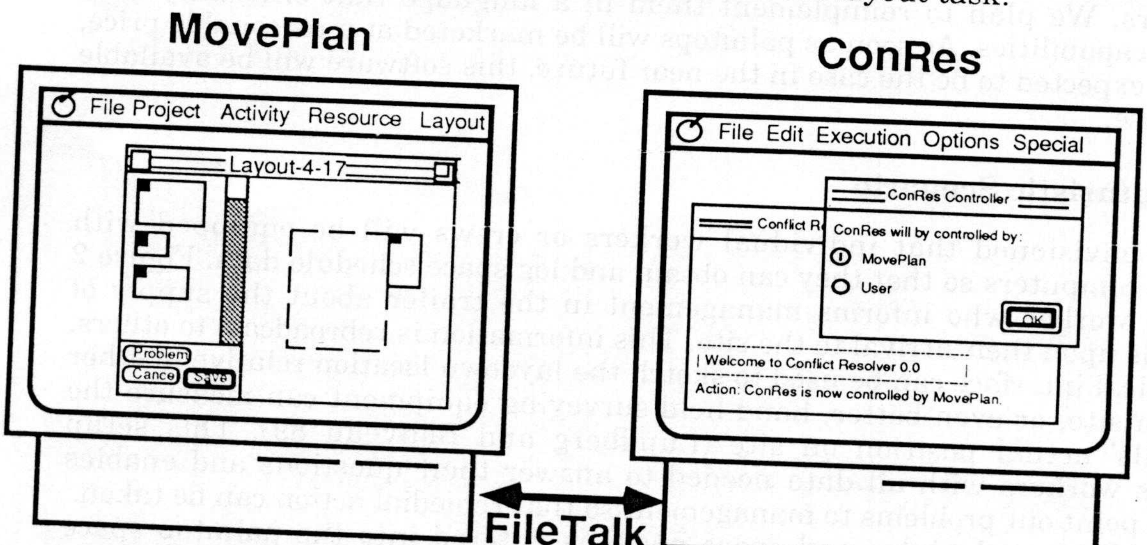


Figure 1. MovePlan–ConRes Interface

### 4.1.2. MovePlan-ConRes

MovePlan has been loosely integrated with a space-schedule conflict resolver, named ConRes (Figure 1). ConRes opportunistically chooses one of several strategies for modifying a schedule so that space needs can be better accommodated in time intervals that are identified as problematic (Tommelein et al. 1993). Such strategies delay one or several activities to remove a resource from the current time frame while minimizing project delay or minimizing the increase in resource idle time, or, alternatively, change an activity's resource use level while minimizing project delay or maximizing the freed-up space. These strategies are by no means exhaustive, nor do they guarantee that a better schedule will be produced. Additional strategies for space schedule conflict resolution are being investigated.

### 4.1.3 MoveSchedule

The MoveSchedule program for space schedule construction tightly integrates and automates the space allocation and scheduling tasks. It is being developed by Zouein and Tommelein (1993). One key feature is that resources are modeled with lead times (the time period over which materials are on site before the activity starts) and safety stocks (the minimum amount of material on site that is maintained at all times until the material is no more needed; when a supply falls below the safety stock, it is replenished). The model also reflects resource depletion during the execution of an activity. It can thus represent just-in-time and just-in-case deliveries.

MoveSchedule will lend itself well to integration with a materials inventory control system, possibly tied to a bar coding system for tracking material arrival and placement in the permanent facility.

## 4.2. Hardware Needs

In 1983, the BRT pointed out that "Too little use is made of new, cheap micro-computers and software." (BRT 1983, p. 56). While this may still be true, one needs to look ahead and assess how the advent of palmtop computers is to change construction materials management. The above three programs all run on laptop computers. We plan to reimplement them in a language that efficiently uses palmtop capabilities. As soon as palmtops will be marketed at a reasonable price, which is expected to be the case in the near future, this software will be available for site use.

## 4.3. Futuristic Scenario

It is envisioned that individual workers or crews will be equipped with palmtop computers so that they can obtain and log space schedule data. Figure 2 shows a worker who informs management in the trailer about the supply of materials upon their arrival to the site. This information is rebroadcast to others. A graphical interface can be used to sketch the laydown location relative to other items on site, or even better, hand-held surveying equipment can measure the materials' actual position on site (Lundberg and Beliveau 89). This setup provides workers with all data needed to answer their questions and enables them to point out problems to management so that remedial action can be taken.

In addition, schedules and space needs is entered into the palmtop space scheduling tool by crews who plan their next day's work. Pertinent data is abstracted from it and broadcast to others who might detect interference problems or resource conflicts. Mediation software them helps them negotiate priorities.

This setup assumes that data can be entered and retrieved by all palmtops on site. Relatively powerful computers are therefore needed. How such a distributed communication system for on-site materials management will work within the current organizational structures and materials handling practice (e.g., assigning the appropriate responsibility and authority for adding, deleting, and modifying data) is a wide open area of research.

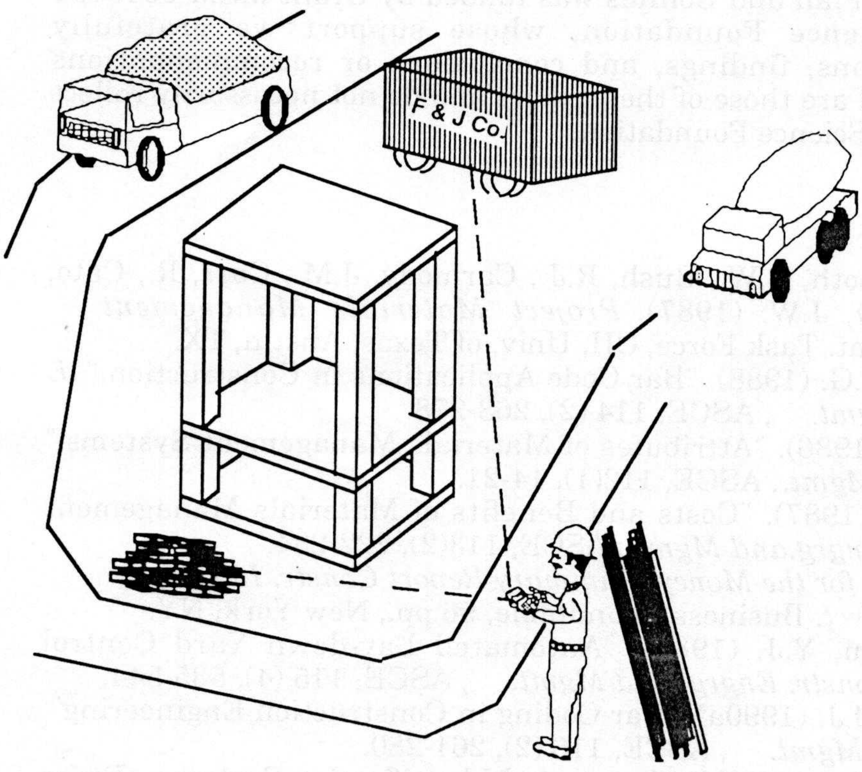


Figure 2. Futuristic Scenario for Use of Space Schedule Data

## 5. SUMMARY

Ten years ago, the Business Round Table concluded that "The material and equipment built into industrial and commercial facilities and power plants cost an estimated $82 billion in 1979—some 60% of the total cost of those structures. But a CICE survey concludes that a significant part of the labor cost that went into that construction was wasted because materials and equipment were not available at the site when they were needed. That is the kind of foul-up modern management systems can minimize." (BRT 1983, pp. 29-30). At present, microcomputers and management techniques have not been exploited to the maximum of their potential. In the mean time, the technology has leaped forward and even more radical improvements to construction practice can be expected from the laptop and palmtop computer revolution. The desired use of such devices on site must therefore be researched, in anticipation of their wide-spread availability. Accordingly, the MovePlan, ConRes, and MoveSchedule models were briefly introduced, to show how space and schedule data can effectively be used in construction operations planning.

Issues pertaining to data collection for space scheduling, scheduling progress control, and data dissemination were discussed for obtaining an original and adjusting an existing space schedule if plan deviations become intolerable. A futuristic scenario illustrated the use of palmtops for space scheduling on site.

## 6. ACKNOWLEDGMENTS

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