Linear Scheduling and Visualization

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There has been a resurgence of interest in linear scheduling as a practical and visual tool for use in planning transportation construction projects. Network analysis techniques and bar charts do not provide the planner with an adequate means of analyzing the way in which crews move through time and space. Linear schedules can be used to overcome this problem. A review of linear scheduling research is presented to show the need for a standard format that combines the best of prior research and experience. Recommendations covering this format and the methodology to be used in a proposed standard format are presented. Three basic symbols—bars, lines, and blocks—are developed for use in drawing linear schedules. Some thoughts on specialized linear scheduling nomenclature are provided. It is concluded that the process of drawing bars, lines, and blocks on a linear schedule places the primary focus on planning and returns a measure of credibility to scheduling.

Major problems arise in the scheduling of transportation projects because of the flexibility available when planning the work. Projects such as highways, bridges, tunnels, and railroads have a significant linear dimension, and the work is therefore spread over a large area. Planning decisions as to where to start the project and how to pursue the work in an orderly fashion are extremely important because they are usually not subject to more than a few nonnegotiable technical constraints.

This flexibility in planning contrasts starkly with the heavily constrained situation that arises in building or other forms of vertical construction. Where to start and how to proceed is, by and large, dictated by the fact that foundations and the first floor come first and that subsequent floors follow in a given pattern with a limited amount of flexibility available in the macro-level planning process. The key to success on these projects lies in scheduling individual activities in a tightly constrained sequence. This contrasts strongly with linear construction, where the key to success lies in the planning needed to optimize flexibility in the use of space and time.

This paper shows how carefully designed linear schedules can be used as a tool in the planning that must precede the development of a realistic construction schedule. The focus is on a return to basics, and emphasis is placed on planning by visualizing the flow of processes that use time, space, and resources to produce quality construction on time and on budget.

IMPORTANCE OF VISUALIZATION

Most transportation construction projects are one-time and largely unique efforts of limited time and duration involving work of a nonstandardized and variable nature (*1*). Visualizing the flow of work through time and space is extremely important, and it is better to plan and replan than to produce a poor plan and experiment with it during project execution. The planner's ability to visualize the flow of work and a simple graphical tool to capture and record his or her thoughts make it possible to build and rebuild the project many times on paper. Field execution occurs only once, and neither time nor money is available to experiment with construction procedures that should have been optimized in the planning process.

Network analysis techniques and other mathematical approaches seldom allow or even require planners to have a complete feel for the project in the planning phase. Commercial software packages cause the planner to focus on providing the required inputs. Planning is seen as a rote, time-consuming process of dividing the work into a series of activities (less than 10 days long as required in many contract specifications), adding logic constraints and resource requirements, inputting the whole lot—via a spreadsheet list for increased efficiency—and seeing what comes out. Creativity in visualizing the flow of work and testing alternative strategic plans is smothered by the challenge of providing the input and understanding the output. Realism in planning is lost, scheduling becomes a farce, and execution proceeds according to the demands of the moment.

Bar charts have long been an effective tool for recording the planner's intentions on a time scale. The challenge of producing a well-drawn and detailed bar chart on a single, though large, piece of paper certainly causes the planner to visualize the flow of work and structure strategic alternatives with care.

The single dimension, time, presented on the x-axis of most bar charts reduces their effectiveness when the planner requires a clear vision of how work will flow from location to location. Linear schedules of the nature described in this paper overcome this limitation by providing a mechanism to show both the time and the location at which operations are to be performed. This allows the planner and, subsequently, users of the plan to develop a clear vision of what is to happen, when it is to happen, and where it is to happen.

LINEAR SCHEDULING TECHNIQUES

An awareness of the fact that the traditional network is not the best tool for the planning of linear projects and the shortcomings of bar charts in today's complex world has led to a resurgence of interest in techniques to assist in planning these projects (*2*). The techniques that have been developed are generally referred to as linear scheduling methods. Their origins are not clear, and there may have been multiple origins, pos-

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sibly in different countries. Many were originally devised to solve industrial production problems, and their use in the construction industry is a rather recent event. The techniques include a multitude of variations and a variety of acronyms (*3*).

Projects that are generally characterized as linear may be divided into two categories. The first includes projects that are linear due to the uniform repetition of a unit network of activities throughout the project. Multiple housing projects involving the repetitive construction of similar houses are a good example of this category. The second category includes projects that are linear essentially due to their physical layout. Highway projects, tunnels, railroads, and many transportation projects are excellent examples of this category. These projects are generally not characterized by the uniform repetition of a unit network, and they involve a number of activities that are discrete or unique in nature. The distinction between repetitively linear and physically linear projects provides a good basis for classifying the techniques, which have been used with varying degrees of success in the construction industry.

Techniques for Projects Characterized by the Repetitive Use of a Unit Network

Construction activities on linear projects are similar to the continuous manufacture of many units on a production line. The development of a prototypical unit network is helpful for these projects. Some techniques such as line-of-balance (LOB) scheduling and the vertical production method (VPM) use the concept of a unit network to graphically depict the construction schedule.

LOB

The LOB technique was developed by the U.S. Navy Special Projects Office in the early 1950s (*4*). It was first applied to industrial manufacturing and production control, where the objective is to attain or evaluate a production line flow rate of finished products (*5*). LOB has proven itself an effective management tool for steady-state production activities (*6*).

The LOB technique requires the following three inputs (*7*), which are usually represented graphically: (*a*) a unit network (production diagram) showing activity dependencies and time required between activity and unit completion, (*b*) an objective chart showing cumulative calendar schedule of unit completion, and (*c*) a progress chart showing the completion of the activities for each unit.

Al Sarraj (*8*) "formalized" the LOB method by developing its algorithms. He states, "By adopting the method in its formalized form, there is no need for any diagrams to be drawn as a means of defining the schedules." This approach, though mathematically and technically elegant, is counter to many of the arguments made in favor of graphical presentation to assist in visualizing the flow of work. LOB has been used in some linear construction projects characterized by the repetitive use of a unit network (*3,7,9*). Its widespread use on all types of linear projects is, however, doubtful because there are many factors inhibiting representation of the entire project by repetition of a unit network throughout the duration of the project. Kavanagh (*10*) states that LOB techniques "were designed to model simple repetitive production processes and, therefore, they do not transplant readily into the complex and capricious construction environment."

Ashley (*11*) comments on the usefulness of LOB in complex linear construction projects and states that "Learning curve effects, 'come back' delays, constraining resources, and stochastic activity durations, all important characteristics of repetitive-unit construction cannot be modeled by the LOB technique."

VPM

VPM was developed by O'Brien (*12*) specifically for use in construction of high-rise buildings. O'Brien recognized the importance of using a network to schedule basic preparation work such as site work, foundations, and structures to the first typical floor. He pointed out that the whole project momentum changed with the construction of the first typical floor and that, from this point onward, the work could be presented by a unit network for a typical floor.

The diagram that O'Brien (*12*) and O'Brien et al. (*13*) used to graphically portray VPM is, in many ways, similar to the linear scheduling diagram discussed in the next section. The horizontal and vertical axes are used to depict time and floors, respectively, in the high-rise building.

Techniques for Projects Characterized by a Linear Physical Layout

Some construction projects are linear essentially due to their geometrical or physical layout. They are not characterized by uniform repetition of a unit network and generally involve a number of activities that are discrete in nature. The execution of the linear activities is often not in a uniform fashion from the start to the end of the project.

Graphical techniques such as the linear scheduling method and the time-space scheduling method have been successfully used to plan and schedule projects of this type. Gorman (*14*) was among the first authors to suggest the use of a "time versus distance diagram" to achieve better communication of schedule information through visual impact in rapid transit, highway, and pipeline projects. This diagram had location on the x-axis and time on the y-axis. Clough and Sears (*1*) adopted essentially the same format when presenting "a bar chart for repetitive operations" in their book. The example used shows repetitive activities for a pipeline relocation drawn as straight lines on a graphical layout.

Johnston (*5*) first used the term "linear schedule method" in a research paper that focused on highway construction. He discussed the basic elements and concepts of the linear schedule method and used the x-axis to measure time. The y-axis plotted location along the length of the project. Activities were plotted as a series of diagonal lines with linear productions rates used to define the slope of the lines. Barrie and Paulson (*15*) present an essentially similar diagram as a "linear balance chart" but also present a "horse blanket schedule" based on schedules used on the Washington, D.C., and Atlanta, Georgia, rapid transit projects. This schedule showed distance on the x-axis and time progressing upwards on the y-axis.

Chrzanowski and Johnston (*16*) provided an excellent example of linear scheduling applied to a highway project in North Carolina. They show the survey stations along the project plotted on the x-axis with time progressing downward on the y-axis.

Vorster and Parvin (*17*) adopted an approach essentially similar to that of Barrie and Paulson to develop a linear scheduling format for highway construction. This format has a strong visual impact and an intuitive linkage to the highway construction process:

1. The x-axis or horizontal dimension of the linear schedule is used to measure distance along the project in a manner consistent with the actual physical layout of the works.
2. The y-axis or vertical dimension of the schedule diagram is used to measure time. Early dates are placed at the bottom so that early operations such as clearing are drawn below later operations such as surfacing to provide an intuitive linkage with the layered sequence in which field operations actually occur.
3. A set of three simple graphical symbols (bars, lines, and blocks) are used to show the way in which the planner has provided time and space for each of the logically sequenced operations.

Bafna (*18*) expanded on this work to develop what will, it is hoped, become a standard format for linear scheduling on transportation-type construction projects that have a significant linear or distance dimension.

A STANDARD FORMAT AND SYMBOL FOR LINEAR SCHEDULES

Strong arguments have been put forward to support the notion that successful planning can only be achieved if the planner is able to clearly visualize the flow of work and resources needed to complete a given project. Linear scheduling has been proposed as a simple graphical tool that can be used to capture the planner's thoughts. Research to date has been reviewed to arrive at a format optimizing the visual impact of linear schedules when used on transportation construction projects.

The proposed format for linear scheduling is described in the hope that this will lead toward a measure of standardization. The methodology proposed is simple but will add to a better understanding of the technique and the results obtained.

An example will be used to describe the concepts discussed. The project is 10,000 ft long (Station 0 to Station 100). The start date is August 1, 1991, and the end date is April 1, 1992. The work includes a retaining wall between Stations 15 and 25, a bridge at Station 65, and a number of regular grading and paving operations.

Allocation of Axes

The clear distinction between LOB and linear scheduling showed that in most, if not all, linear schedules the horizontal (x-) axis is used to depict distance or location along the project. This is logical because it creates a strong intuitive and visual link between the work and the diagram that displays the intended plan or action.

Time is allocated to the vertical (y-) axis with early dates placed at the lower end of the scale. This further reinforces the intuitive and visual linkage between the work and the linear scheduling diagram in that early operations such as clearings, drainage structure construction, and grading appear below the later, and, in a physical sense, upper operations such as subbase, base, and surfacing.

The selection of scales and labels for use on the axes depends on the level of detail desired in the diagram. Division by station on the x-axis and by month on the y-axis is commonly used. Major and minor labels are used to mark the axes and scale points. Figure 1 shows the allocation of axes and labels for the example.

Graphical Details

Details regarding location and time aspects can and should be added to the linear scheduling diagram at the onset. They remind the planner of the physical aspects of the work and ensure that the planning process takes place within a proper framework.

Plans

At times it will be advantageous to add a rough project plan to the top of the linear schedule to show information regarding the location of ground features such as access points intersections, crossovers, bridges, and culverts. The plan should be drawn to the same scale as the horizontal axis and be approximately aligned with it. Figure 2 shows the addition of the project plan to the top of the schedule being developed for the example project. It clearly shows the location of the retaining wall, which spans from Stations 15 to 25, and the bridge at Station 65.

Profiles

It can be advantageous to add a profile of the project at the top of the scheduling diagram. This profile should be drawn

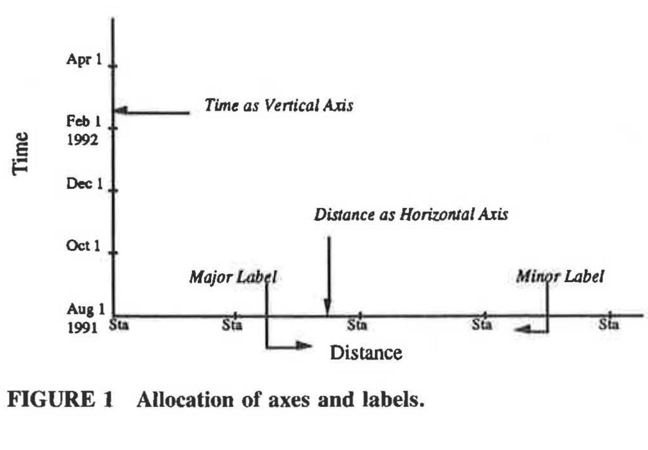

FIGURE 1 Allocation of axes and labels.

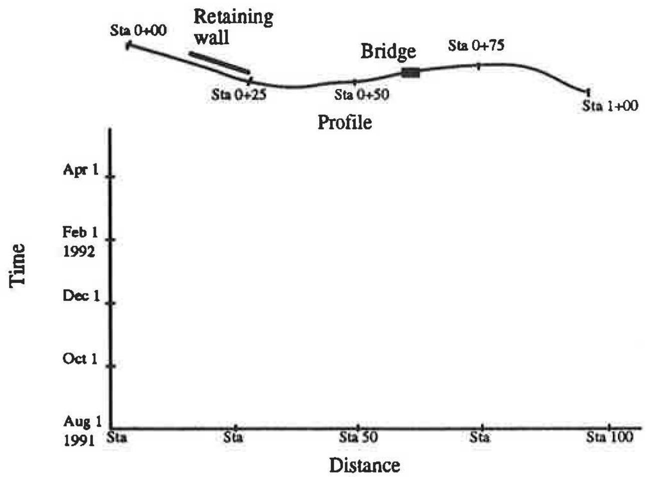

FIGURE 2 Addition of a rough plan to the linear schedule.

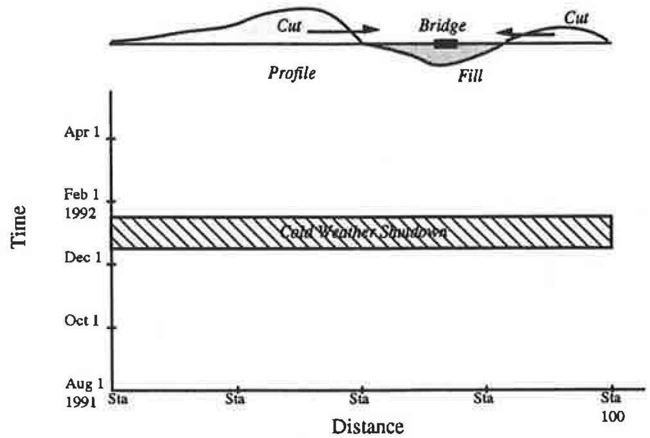

FIGURE 4 Season constraints.

with the same horizontal scale as used for the distance axis and should be aligned with it. The profile should show such features as cuts and fills, drainage structures, bridges, and other points of interest. The profile helps in visualizing the earthwork operations because the cut and fill locations are easily seen. A profile for the example project is shown in Figure 3. The profile shows cuts from Stations 0 to 50 and 80 to 100 and a fill from Stations 50 to 80. The addition of arrows helps in identifying the flow of material.

Season Constraints

Construction projects frequently depend on seasons, since almost all the construction work is executed outdoors. It is therefore advantageous to mark on the linear schedule the time periods when the work cannot be carried out because of bad weather. Figure 4 shows how an extreme cold weather period from December 15, 1991, to January 15, 1992, can be represented to remind the planner that this period is not available for work.

Access Constraints

There are situations in the field when access to the entire project is not simultaneously available to the contractor. Marking the access profile on the linear schedule will serve as a constant reminder of the unavailability of sections of the project and will help in planning operations accordingly. Figure 5 shows that the section between Stations 75 and 100 of the example project will not be available for 2 months from the project start date.

Sight Lines

Addition of vertical and horizontal sight lines to the scheduling diagram makes determination of the start and end dates and start and end station of an activity easier. Sight lines can be conveniently spaced on both the axes according to the required level of detail. Figure 6 shows the addition of sight lines to the example. Horizontal sight lines are placed at every second month and vertical sight lines after every 25 stations.

Sight lines may be added at dates or sections of special significance. A horizontal line is frequently used to mark the end date, and special vertical lines can be added at the end

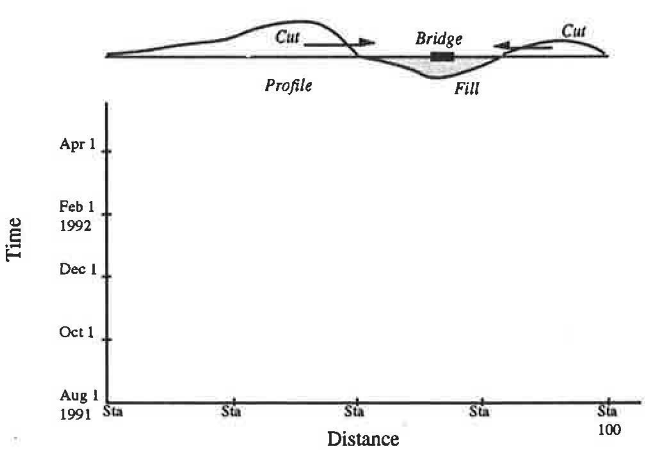

FIGURE 3 Addition of a profile to the linear schedule.

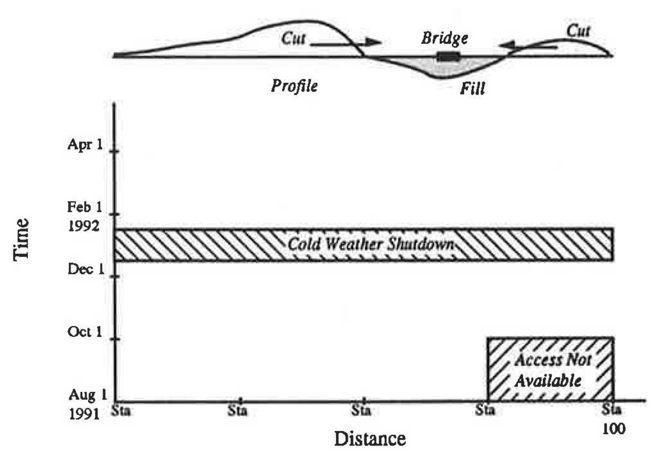

FIGURE 5 Access constraints.

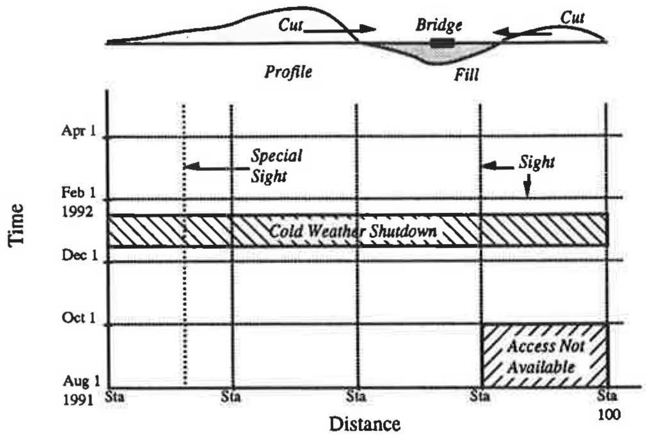

FIGURE 6 Sight lines.

of a significant section of the project. Figure 6 shows a vertical line drawn at Station 15, which, in conjunction with the regular sight line at Station 25, marks the start and end of the retaining wall.

Standard Symbols

The axes, graphical details, and sight lines provide a structure to the arena within which the planning must take place. Three relatively simple symbols geared to the nature of the work being planned can be used by the planner to depict the flow and interrelationships of the work.

Bars

Some operations, such as bridge or culvert construction, require that work be performed at a given location for a relatively long period of time. These operations are best represented by bars defined by the location of the work and the time needed to complete the tasks represented. Figure 7 shows a bar with location appropriately placed on the distance scale and start date, end date, and duration appropriately placed on the time scale.

Lines

Lines are drawn to track the movement of a crew or a particular operation through the job as time progresses. Operations such as the various base course layers surfacing or track laying can be effectively represented by lines because the work moves ahead at a relatively steady rate. The slope of the line represents the rate of progress; a flat slope represents substantial progress in a given period, and a steep slope represents little progress over time. Figure 8 shows the use of a line to represent operations on a linear schedule. The line from A to B has a steeper slope than the line from B to C to show a slower rate of progress.

Blocks

Blocks are used to represent operations that do not move smoothly from location to location. The crews thus occupy a substantial portion of space for a given period of time. Grading operations of various types are well represented by blocks because it is not possible to pinpoint the location at which work will take place at a given time. Other symbols, such as bars or lines, may fall within a block representing another activity, but care must be taken to ensure that the tasks depicted do not compete for the same space at the same point in time.

Figure 9 shows how a block may be used to represent the time and space needed to perform the work lying between A and B on the distance scale.

Additional Graphical Conventions

Linear scheduling is a planning tool designed to capture the thought processes of the planner seeking to optimize the use of time and space. The standard format and symbols described in this section provide a starting point for the creative thought needed to develop and document the plan of operations for a major project. Discussion of all the possible techniques, symbols, and styles used to draw a linear schedule within the framework presented here is clearly beyond the scope of this

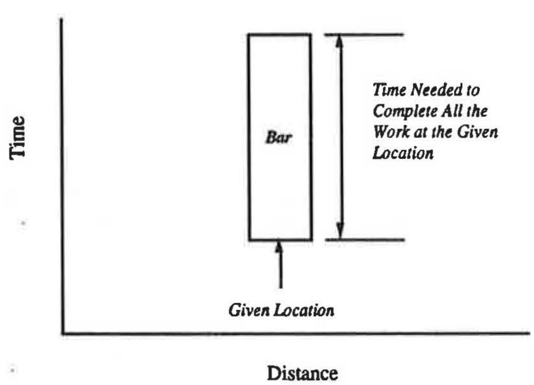

FIGURE 7 Bar used to represent operations on a linear schedule.

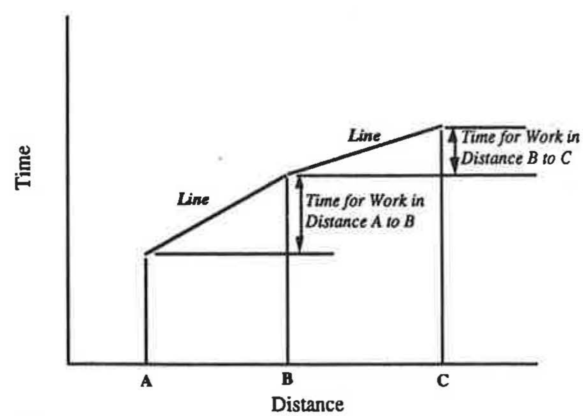

FIGURE 8 Lines used to represent operations on a linear schedule.

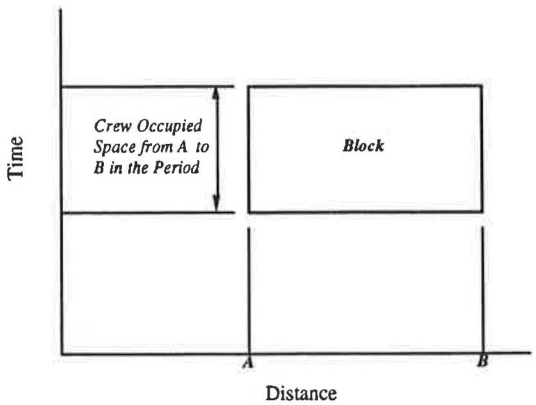

FIGURE 9 Block used to represent operations on a linear schedule.

paper. Every planner uses his or her own imagination to present a solution to a given problem.

Three examples will be given:

1. Colors, fill patterns, and line types: The visual impact of the schedule and the ability to trace the flow of crews and work can be greatly enhanced by the use of different colors, fill patterns, and line types. Figure 10 shows the visual input and clarity available by using fill patterns and line types.

2. Special symbols for earth movement: The judicious use of figures, arrows, and notes can modify the blocks used to depict grading operations to the extent that they replicate a standard grading diagram. The use of these special symbols is shown in Figure 11. Incorporating these can bring to life the intent of the overall earth-moving operation.

3. Multiple adjacent schedules: A number of schedules can be drawn side by side to the same time scale to depict nonlinear sections of the same project or show how crews move from one project to another in a multiple-project situation. Figure 12 shows how the two project components can have the same time scale with different locations. This side-by-side look can provide an overall feasible plan for moving crews from one location to another.

CONCLUSIONS

Figure 13 shows the planning depth that can be achieved using linear scheduling. A bar chart or CPM schedule cannot provide the same level of understanding as a visual schedule. What-if scenarios can be played out to determine options and reduce overall project time. Only when these visual tools are used will linear transportation projects take on a meaning that is readily transferable among all members of the site and office.

Success in the execution of transportation construction projects demands that work be done in an ordered sequence, that production crews be given the time and space needed to perform, and that delays and changes be minimized. The foundation for success in these areas is laid in the planning process, and the planner must visualize how the space provided by the physical dimensions of the project can be used to achieve a desirable construction sequence. Neither networks nor bar charts are of much value in this regard as they cannot represent space and time in a visual and easily understood format.

There has been a resurgence of interest in linear scheduling as a tool to help the planner capture thoughts and commit them to paper. The standard format proposed earlier is a product of this resurgence, and a number of complex projects have been planned using the techniques described. The process of drawing bars, lines, and blocks to depict the movement of crews and the interrelationships between activities placed the primary focus on planning rather than simply scheduling these projects and returned a measure of credibility to the resulting project schedules.

Much work needs to be done. Prototype software to integrate linear schedules and networks has been developed and is under test. The software combines the powerful ability of network-based techniques to calculate dates with the best visual and spacial attributes of the linear schedule. The ob-

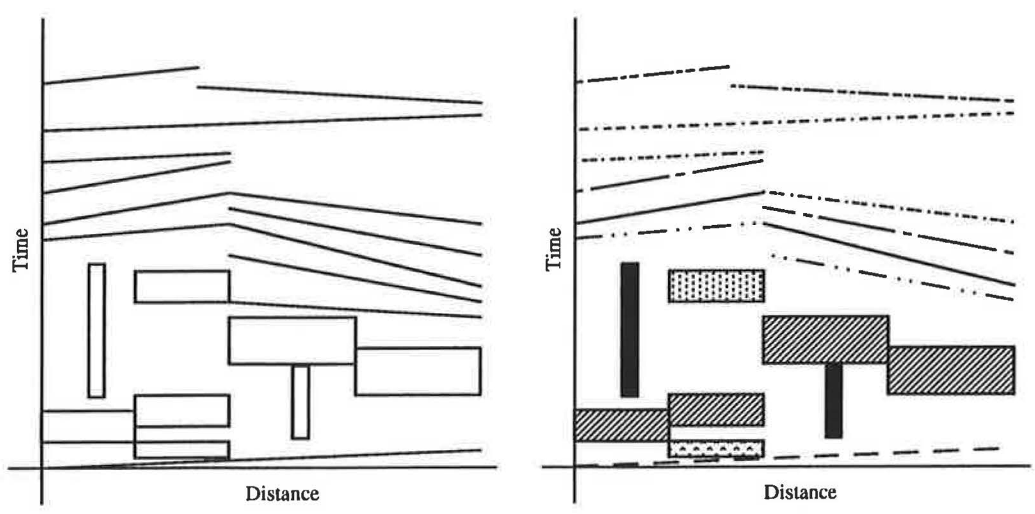

FIGURE 10 Example using fill patterns and line types.

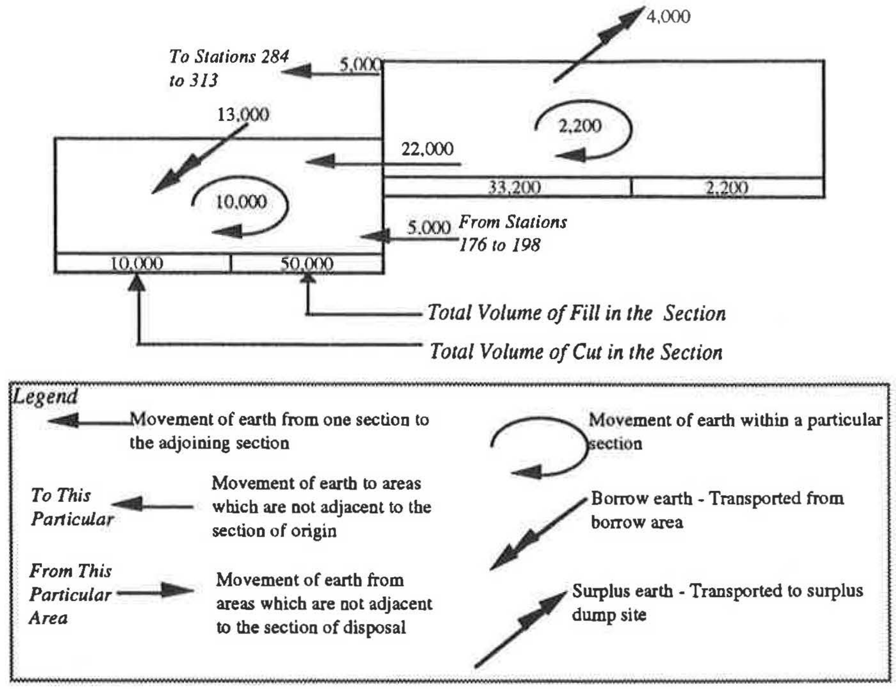

FIGURE 11 Special symbols for earth movement.

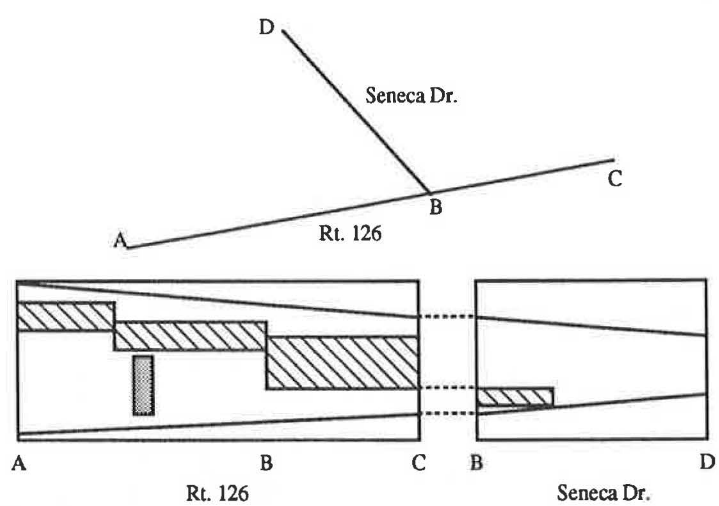

FIGURE 12 Multiple adjacent schedules.

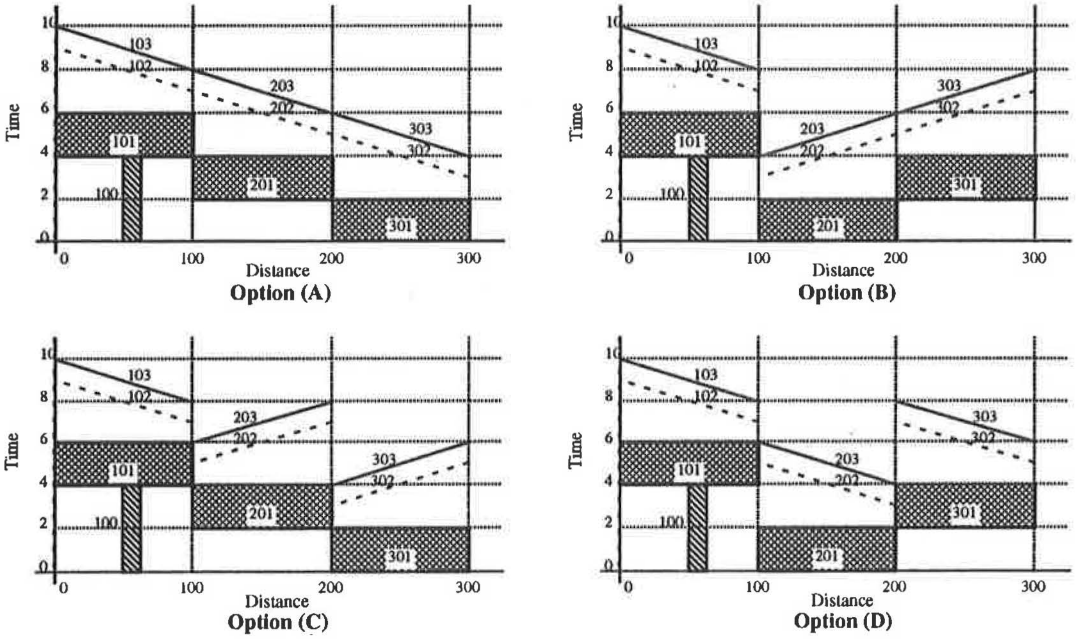

FIGURE 13 Linear scheduling as a graphical simulation tool.

jective is to produce a document incorporating the rigor of network analysis in a clear, intuitive visual display of the planning intent.

Implementation and development of the techniques presented in this paper are progressing. The results obtained to date have been of benefit to both owners and contractors.

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