Comparison of Linear Scheduling Model (LSM) and Critical Path Method (CPM)

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Abstract: Due to an increasingly competitive environment, construction companies are becoming more sophisticated, narrowing their focus, and becoming specialists in certain types of construction. This specialization requires more focused scheduling tools that prove to be better for certain type of projects. The critical path method (CPM) is the most utilized scheduling tool in the construction industry. However, for certain types of projects, CPM's usefulness decreases, because it becomes complex and difficult to use and understand. Alternative scheduling tools designed to be used with specific types of projects can prove to be more practical than CPM solutions. This paper provides a comparison of the CPM and a specialized tool, the linear scheduling model, by identifying critical attributes needed by any scheduling tool both at the higher management level and at the project level. Two project examples are scheduled with each method, and differences are discussed. Conclusions support that specialization of scheduling tools could be beneficial for the project manager and the project.

INTRODUCTION

Due to an increasingly competitive environment, construction companies are becoming more sophisticated. In order to be more efficient and achieve competitive operational advantage, companies are always looking for improvements in equipment features, communication tools, efficient management techniques, and training human resources. For these reasons, construction companies are narrowing their focus, becoming specialists in certain types of construction projects. This specialization requires more focused scheduling tools that prove to be better for certain type of projects.

There are different kinds and varieties of scheduling tools. These tools vary depending on how they represent and analyze activities and their logical relationships. Some of these have been adapted from manufacturing settings—line of balance (LOB)—and are used extensively in the construction industry. Other methods have been used to schedule train arrivals/departures—linear schedules (LS)—and were also adapted to be used in construction. Among these, to name just a few, the most known and utilized methods in the construction industry are:

- Network scheduling type, such as the critical path method (CPM) and project evaluation and review technique (PERT)
- Bar/Gantt chart
- Line of balance (LOB), adapted to construction as vertical production method (VPM)
- Linear schedules (LS) adapted by several methods among which is the linear scheduling model (LSM)

Some of these methods are more efficient than others, depending on the nature of the project to be scheduled. Table 1 suggests which scheduling tool is appropriate for each type of project. Some of these scheduling methods perform extremely well for certain projects but poorly in others. Therefore, some of these tools are very specialized, and their use is limited to a specific subset of projects.

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LSM (Harmelink 1998) is a specialized tool that improves LS by allowing CPM-type calculations. The LSM performs optimally when scheduling linear continuous projects, such as highway construction, because it was conceived to represent and schedule this specific type of project. However, LSM can be very inefficient when scheduling complex discrete projects (bridges, buildings, etc.). CPM is quite the opposite, it is ineffective and cumbersome for scheduling linear continuous projects but extremely effective for more complex and discrete type projects.

Despite this specialization difference, the most utilized scheduling tools in highway construction are the Bar/Gantt chart and CPM. There are several reasons to justify the utilization of these tools (Bar/Gantt chart and the CPM) in highway construction. Some of these reasons are related to analytical capabilities, extensive utilization in other projects, ease of use, good communication, and unawareness of the capabilities and functionality of other specialized methods, like the LSM.

The purpose of this paper is to briefly evaluate and compare network programming techniques and linear scheduling techniques, by specifically comparing CPM and LSM. This comparison will be based on how these two methods incorporated different project management attributes. The comparison framework was developed by first defining a group of ''must have'' attributes that will serve as evaluation parameters for the CPM and LSM comparison. These attributes will be briefly described and discussed in order to understand the basic properties that have to be satisfied by any scheduling tool. These properties are considered in broader aspects of project management, as well as in a narrower application context, such as highway construction. The second step is the comparison of the CPM and LSM along the attributes identified in the first step. This is done using brief examples that illustrate some of the most notable differences between these methods. Lastly, the differences observed, regarding ease-of-use and performance, are discussed.

PROJECT MANAGEMENT AND SCHEDULING REQUIREMENTS

When managing a project the project manager (PM) performs three distinctive steps—planning, resource integration, and execution and control. Planning, as defined by Kerzner (1998a) is ''the function of selecting the enterprise objectives and establishing the policies, procedures, and programs necessary for achieving them.'' He states further, ''project planning must be systematic, flexible enough to handle unique ac-

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TABLE 1. Recommended Scheduling Tool for Different Types of Projects

Type of project	Scheduling method	Main characteristic
Linear and continuous projects (pipelines, railroads, tunnels, highways)	LSM	• Few activities • Executed along a linear path/space • Hard sequence logic • Work continuity crucial for effective performance
Multiunit repetitive projects (housing complex, buildings)	LOB	• Final product a group of similar units • Same activities during all projects • Balance between different activities achieved to reach objective production
High-rise buildings	LOB, VPM	• Repetitive activities • Hard logic for some activities, soft for others • Large amount of activities • Every floor considered a production unit
Refineries and other very complex projects	PERT/CPM	• Extremely large number of activities • Complex design • Activities discrete in nature • Crucial to keep project in critical path
Simple projects (of any kind)	Bar/Gantt chart	• Indicates only time dimension (when to start and end activities) • Relatively few activities

tivities, disciplined through reviews and controls, and capable of accepting multifunctional inputs.'' There are several good reasons or functions for project planning (Kerzner 1998a,b):

- To eliminate or reduce uncertainty risk and change
- To improve efficiency of the operation to gain economical operation
- To obtain a better understanding of the objectives focusing attention to the critical and important issues
- To provide a basis for monitoring and controlling work

In the first stage of the project, as part of the planning stage, the PM at a minimum has to:

- Set the goals and objectives of the project
- Define the work description and instructions (WBS)
- Select the scheduling tool that is suitable for the type of project
- Create the network/sequence of the schedule
- Create the master/detailed schedule
- Determine budgets
- Select time/cost/performance tracking tools
- Set the report/feedback system
- Create a risk management plan

During this stage, the PM will select what scheduling tool to use. The PM will use schedules for representing the plan of action, managing resources (allocating and leveling), analyzing status of progress, and controlling costs of the project. PMs should look for specific features that will address all three of the project management stages—planning, resource integration, and execution.

During the planning stage, the scheduling tool used should provide answers to specific questions regarding activities and processes of a project. What is the expected duration of activities? What are the interrelationships between activities? What is their production rate? How many resources are needed? How much does it cost to perform it? Lastly, what are the existing time conflicts and what are the main task constraints?

This information will be used and updated continuously during the following two stages—resource integration and execution. The ideal attributes of a scheduling tool for the planning stage are:

- Clear representation of activities and their relationship
- Ability to represent and calculate productivity, expenditures and resource utilization
- Determination of the critical path or activities that control the duration of the project

After the planning stage has been completed, the PM engages in the resource integration stage. Balancing the usage of scarce resources is one of the most important and difficult tasks that the PM faces. Time and money are usually the scarcest resources in a project and lots of attention is given to their optimal use. The PM integrates the available resources with the planned schedule until the best compromise solution is achieved. Changes in resources could affect the completion date of the project and increase/decrease costs. Therefore, understanding how changes in resources impact the completion date is paramount. Resource management (allocation and leveling) has always been a difficult task and successful allocation and leveling could be facilitated if the selected scheduling tool is:

- Easy to use
- Able to perform quantitative and qualitative calculations
- Allow planners to understand the impact of resource variation on milestones and completion dates.

Once the planning and resource integration stages have been completed, the execution of the project can start. During this stage, the PM compares actual progress with planned progress by collecting data and updating schedules, as needed. This controlling phase is also used as a feedback instrument that gives managers the opportunity to make changes and corrections to the original plan in a timely fashion. To control and monitor projects, the schedule tool used must be easy to use and update and should give the project manager a clear understanding of any delays and changes that have occurred when compared to the baseline schedule. Along these lines, the two main attributes needed for controlling and monitoring are:

1. Ease of use and updating
2. Facilitates project communication and understanding

The purpose of reviewing the tasks and objectives pursued by the PM in each of the three project stages was to broadly define the ideal attributes of scheduling tools. Once that has been done, the CPM and LSM comparison can be performed.

CPM and LSM COMPARISON

Scheduling a couple of simple construction examples offers a good framework to compare CPM and LSM. The first ex-

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ample is a small concrete bridge, and the second is a small highway rehabilitation project. Both projects were selected, because they represent two different types of projects; the latter is linear and continuous and the former is discrete and noncontinuous. The following sections will briefly describe each project. After the description, a discussion and an evaluation of how each scheduling technique performs with regard to planning and analysis, resource integration, and execution/control dimensions is presented.

Schedule of Bridge Project

A small concrete bridge project was scheduled first by using CPM and then using LSM. For purposes of this example, only eight activities will be considered, and resources will be fixed throughout the project.

1. North foundation. Activity includes excavating, forming, and placing concrete for the abutment's foundations.
2. South foundation (same as north foundation)
3. North abutment construction. Includes activities to construct a concrete abutment (scaffold erection, rebar assembly, concrete placing, and curing).
4. South abutment construction (same as north abutment)
5. Placement of east concrete beams. Concrete beams of 20-m lengths will span from the north abutment toward the south abutment. The direction north-south is called east abutment.
6. Placement of west concrete beams (same as east concrete beams)
7. Placement of prefab concrete forms over beams. Instead of scaffolding for the support of the pavement, prefabricated concrete slab panels will be placed between beams.
8. Pavement. Hand poured concrete pavement over the prefabricated slabs.

See Fig. 1 for a schematic representation of the bridge, and Figs. 2 and 3 for the CPM and LSM initial schedule representation.

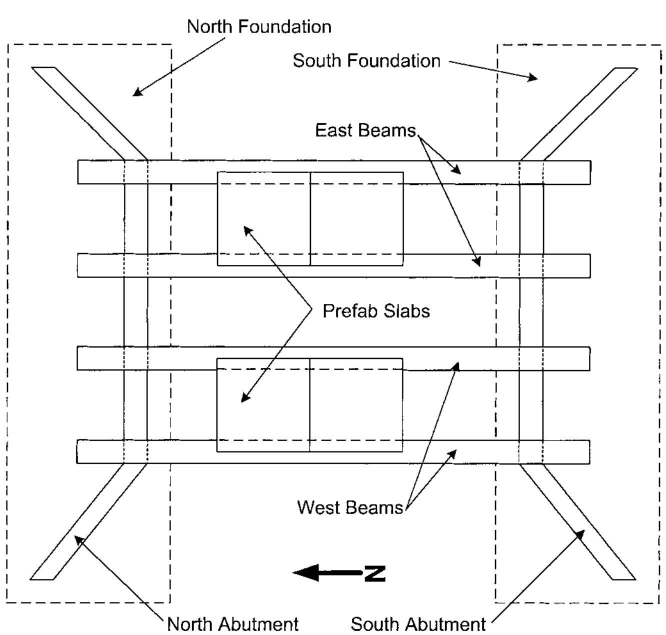

FIG. 1. Bridge Example—Plant View

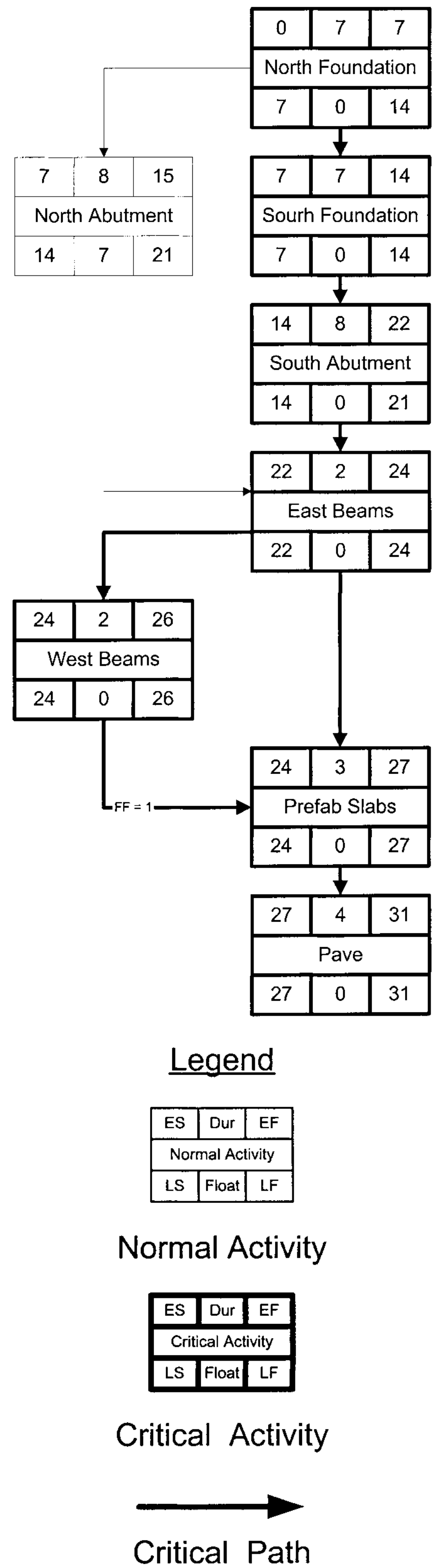

FIG. 2. CPM network for concrete bridge example

Comments and Observations on Bridge Schedule

From the planning and analysis standpoint, both methods allow the representation of the interrelation of activities in a clear and understandable format. However, for activities that occupy the same locations at the same time, the LSM representation is somewhat confusing. This is shown in Fig. 3, where the activity "place prefab slabs" overlaps with "place

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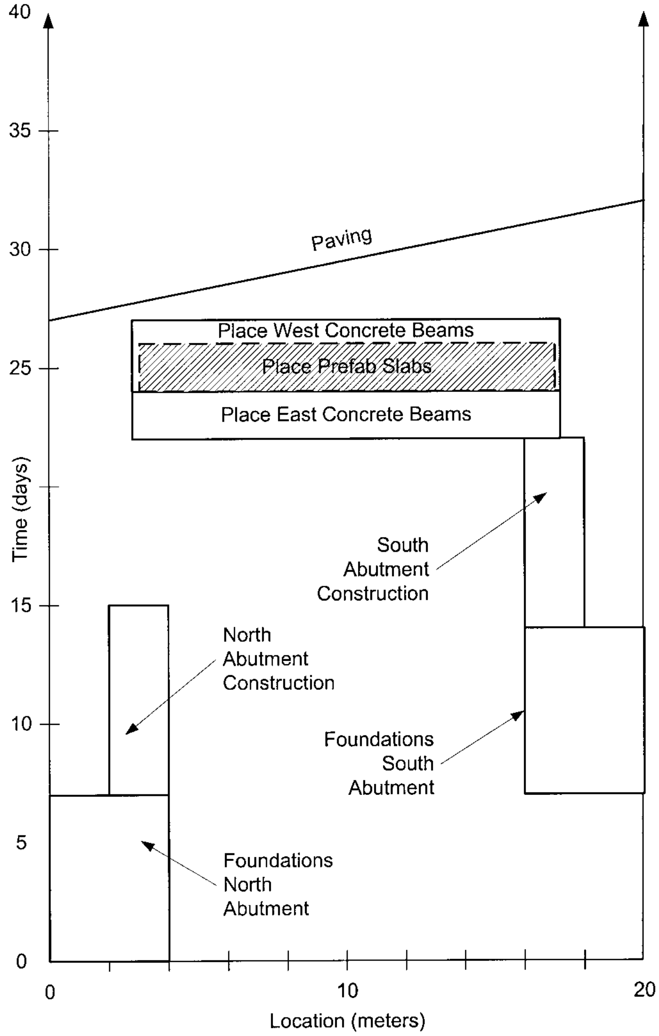

FIG. 3. Linear Schedule Example—Concrete Bridge Schedule

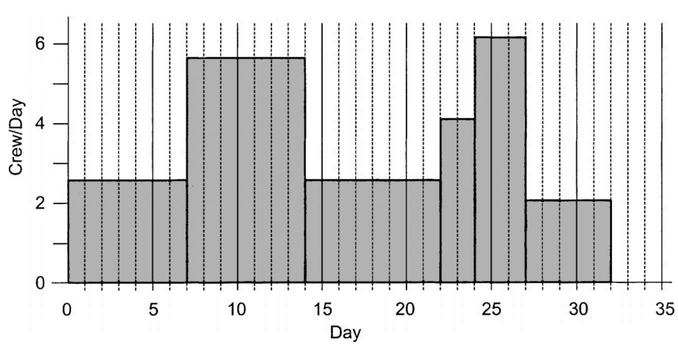

FIG. 4. Crew/Day Usage Graph

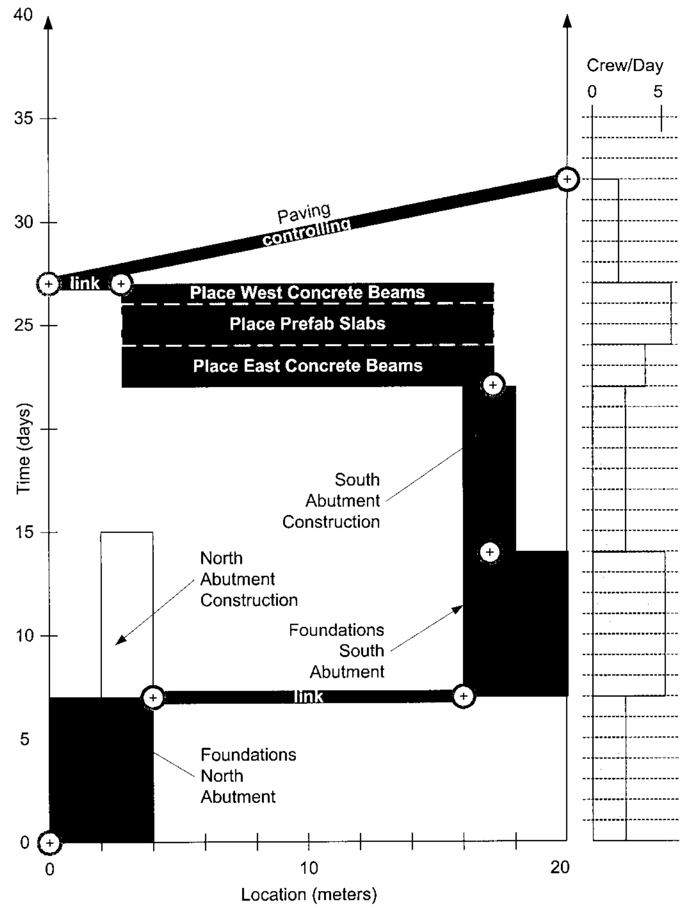

FIG. 5. CAP and Crew/Day Utilization—Concrete Bridge Schedule

west concrete beams.'' The overlapping of these activities is unacceptable, because the LSM method states that such intersection of activities represents a conflict. Nevertheless, the LSM offers an intuitive visual representation of the sequence in which the activities will be performed, as well as the location they will occupy at specific times. Notice that since many of the activities (except paving) occupy the given amount of space for a certain time, most of the activities are discrete blocks. This reduces the advantages offered from the LSM. Both methods allow the identification of those activities that are critical for the on-time completion of the project and which have float. In this example, because the activity ''north abutment'' can be delayed until the ''south abutment construction'' activity is completed, it is not part of the critical path or CAP in either CPM or LSM.

Resource management with CPM is commonly done by plotting resource usage per day in a bar chart diagram. Fig. 4 shows a bar chart representing the man-hours spent in each activity of this project. This graph must be viewed together with the CPM network in Fig. 2 to understand how moving resources from one activity could affect other activities. In the LSM, representation of resource usage is not much different than that of CPM, because it also plots resource utilization per day in a bar chart diagram. However, the LSM combines this resource utilization graph with the schedule (Fig. 5), which allows planners to visualize the resource usage per day together with the schedule of activities. On the other hand, LSM has the same limitations of CPM regarding how shifting resources will affect different activities. This limitation is perhaps greater for LSM, because there are no LSM multiple resource allocation and leveling methods and algorithms, similar to those that have been developed for CPM. Since resource allocation is one of the most critical tasks for the PM, LSM is at a disadvantage against CPM.

Once the project starts, there is no significant difference between CPM and LSM regarding following and updating progress. Even though the LSM schedule offers a good representation by visually comparing the baseline schedule against the actual schedule, there is no additional benefit by using LSM. Most of the activities occur in blocks, therefore, updating will have to be done in the same way it is done with CPM, based on percent of completion of activities. Percent completion involves extra calculations for the field engineer, and most of the time involves judgment as to what percentage of completion should be assigned to each activity.

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Schedule of a Small Road Rehabilitation

A one-lane road needs to be repaved. Resources are also fixed throughout the duration of the project. For purpose of this example, only three activities will be scheduled:

1. Remove old pavement
2. Sub-base replacement and leveling
3. Pave

Both CPM and LSM schedules are shown in Figs. 6 and 7.

In terms of project planning and analysis for linear projects, the LSM schedule accurately represents the inherent space-time relationships of the project. To moderately approximate this detail with CPM, activities have to be segmented creating further representation and calculation complications. In order to illustrate this important difference, two different CPM networks were determined for this project (Figs. 6 and 8). As mentioned before, Fig. 6 represents the three-activity network schedule of the project. This representation fails to capture important time-space relationships between activities, because no consideration was given to the location in which these activities will be performed. Fig. 8 is a CPM network made by segmenting the activities in order to approximate the LS and the CAP calculated with the LSM shown in Fig. 7. It can be seen in Fig. 8 that this CPM network becomes more complicated due to a cascade effect of activities and multiple complex start-to-start (SS), finish-to-finish (FF), and finish-to-start (FS) relationships. This effect is greatly amplified when dealing with more activities and when a finer segmentation is needed in order to locate critical locations vital for the project.

In general, activity durations are directly impacted by the amount of resources required to complete any activity. Change in productivity impacts duration. In a LSM, changes in productivity are represented by changes in slopes of the lines that represent activities. This change in slope can affect the controlling path and ultimately change the total duration of the project. Because of the layout of space-time, LSM represents the relationship of activities that cannot be easily determined with CPM. Furthermore, LSM allows changes in start and end times of activities and productivity in ways that will guarantee the continuity of the activity. By analyzing the road rehabilitation example, two different cases can be identified for explaining resource management scenarios.

Case 1

Case 1 assumes that activities cannot change their productivity (fixed by technical requirements) but can be split (Fig. 9). Segments that are not in the CAP can start at later times (A′ and A″) as long as the least distance (LT) from any of these activities to change and activity B is less than the actual LT between A and B (LT = 5). In order to accurately describe these options with CPM, some of the SS restrictions have to be removed in order to allow activity splits. In addition, looking at the late start and late finish of the different segments will also be helpful (A1, A2, A3, etc.).

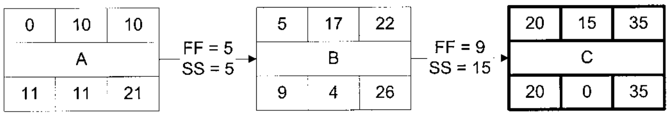


FIG. 6. Basic CPM Three Activity Network

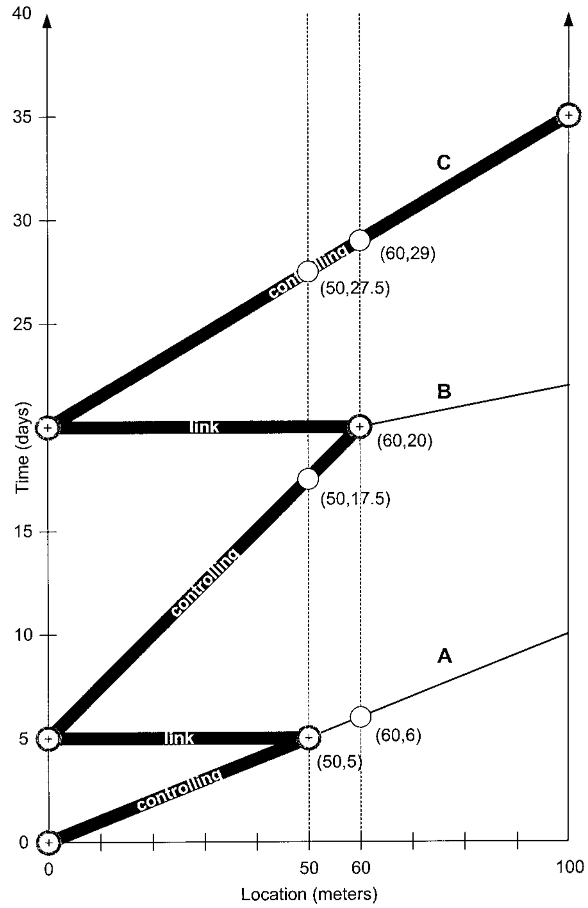
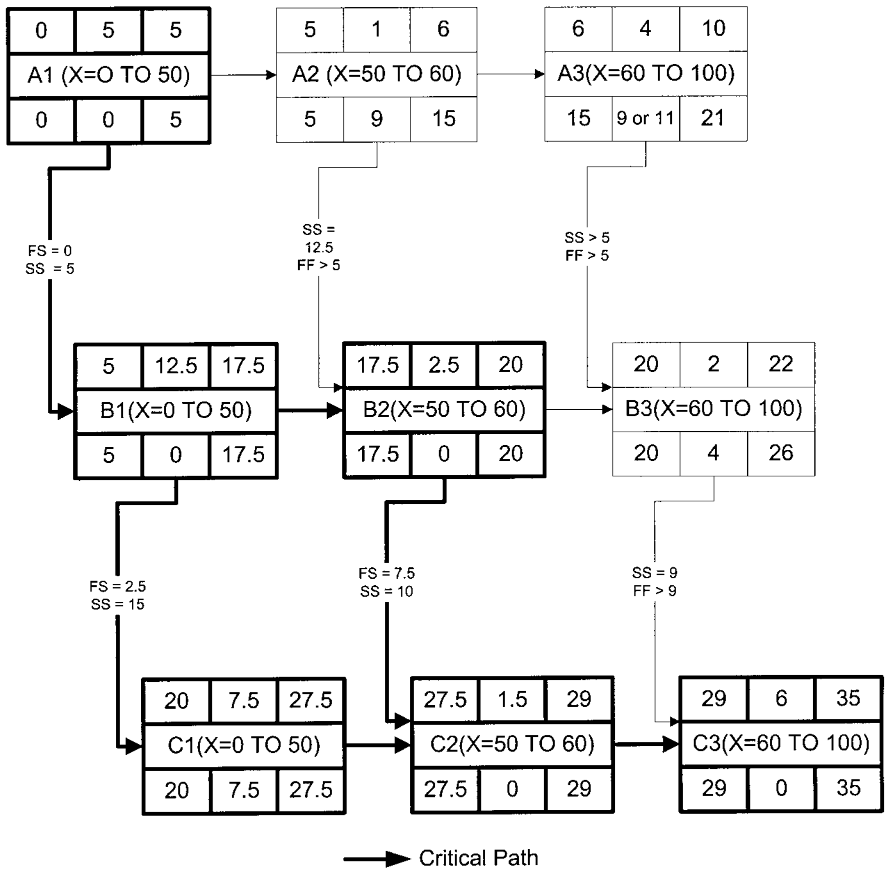


FIG. 7. Linear Schedule Example—Controlling Activity Path in Bold

Case 2

Case 2 assumes that productivity can change, because resources in each activity can be added/removed. Total resources are not interchangeable between A, B, and C. Therefore, removing resources will change durations of float activities and reduce costs but will NOT change the total duration of the project. In this case, LSM demonstrates how easy it is to determine the minimum (HOW MUCH) productivity required, WHEN in time, and the location WHERE productivity can be reduced. For example in Fig. 10, activity A had allocated 10 resources to achieve productivity of 10 m/day. Assuming linear correspondence between resources and productivity, the minimum number of resources that activity A should have is 5 or a productivity of 5 m/day (A_1^+), if no changes in activity B's productivity is done. If reduction of B's productivity is allowed (B^+), the minimum productivity of A would be 3.125 m/day (A_2^+). The only way that CPM would be able to calculate these productivity changes would be through analyzing each segment and how each interacts with the prior segment and further segments. This process is cumbersome even in a simple example such as the one shown.

Using the original schedule as a baseline, project control and update can be performed by plotting progress on top of the baseline schedule (Fig. 11). Discrepancies between planned and executed activities are easily observed. In addition, the only information needed for updating is the location at which the activity is being executed at the updating time. These are easily taken from the field, and no extra calculations are needed. In CPM, however, this feature is not available, and as mentioned in the prior example, project control is done based on information about percent completion of each activity. In this particular type of project, this issue makes it difficult to



(Note: SS = start-to-start; FF = finish-to-finish; FS = finish-to-start.)

FIG. 8. CPM to Represent CAP from Fig. 6

track projects and only offers one dimension of the information.

COMPARISON RESULTS

In addition to the general performance evaluation done by scheduling two different projects, a summary of the most notable differences between methods is presented in Table 2. All three project planning stages, and how each method satisfies each of the attributes that are important for a PM, are shown in Table 2. From Table 2, four things seem to be the most important issues of this comparison.

1. The greatest significant strength of the LSM over CPM is its visualization features and ease of communication for specific types of projects. Since communication ranks very high among the PM's objectives, the LSM is poised to be of significant value to a PM for specific types of projects.
2. The LSM lacks some resource management (allocation and leveling) capabilities. Although LS techniques have been around for a long time, LS did not offer strong analytical capabilities. This was solved when the LSM was developed. On the other hand, CPM has been developed thoroughly. Extensive research has been done in the area of resource leveling and resource allocation geared towards network planning tools, such as CPM/PERT, and advancing its capabilities to levels where they have become the preferred tools for resource management. In contrast, very little work has been done for LS in the same area. The more relevant and recent works done are resource leveling in LS using linear programming (Mattila 1997) and heuristic optimization using Tabu search for resource leveling (Liu 1999). Both works are based on LSM and assume that the CAP does not change. This assumption greatly simplifies the task of conceptualizing the problem, but it would be more useful if the effects of resource changes could be seen in the CAP.
3. CPM is appropriate when time-space relationship occur in different dimensions that cannot be represented in a two-dimensional format.
4. There is no method to incorporate duration and production uncertainty into LSM schedules, as PERT does for network based scheduling methods such as CPM.

CONCLUSIONS

Two different scheduling methods were compared based on their performance along three important stages of project management. The framework for this comparison was constructed by determining a list of attributes that the ''ideal'' scheduling tool should meet and then by actually scheduling two different example projects. Based on these projects, the two methods were evaluated and a comparison was made. Results from this comparison are summarized in Table 2.

With the use of two simple examples, it was shown that planning is facilitated using LSM, because it is visual and intuitive. For very specific projects (linear and continuous), LSM is superior to CPM. However, CPM is a more complete

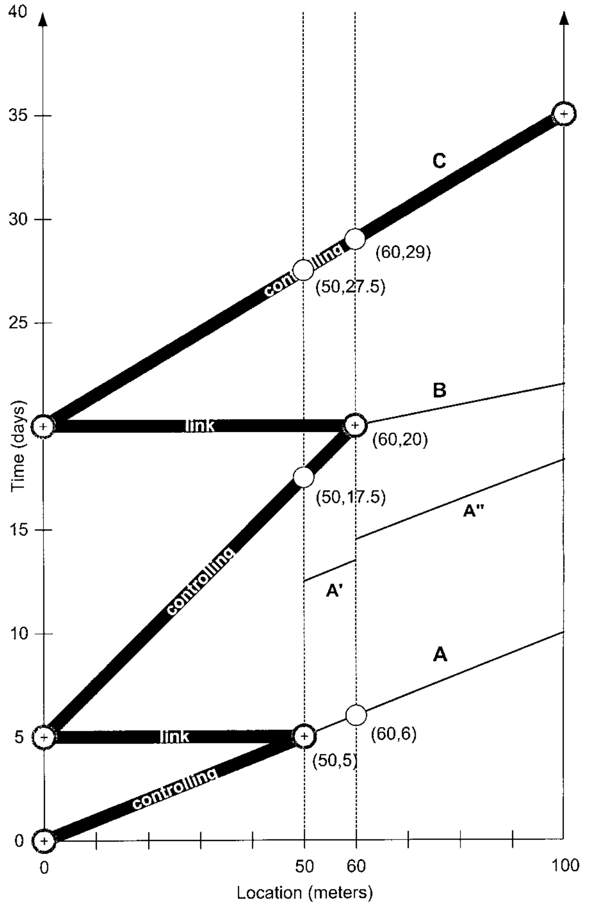


FIG. 9. Moving Linear Activities with Float—Resources Constant—Splitting Allowed

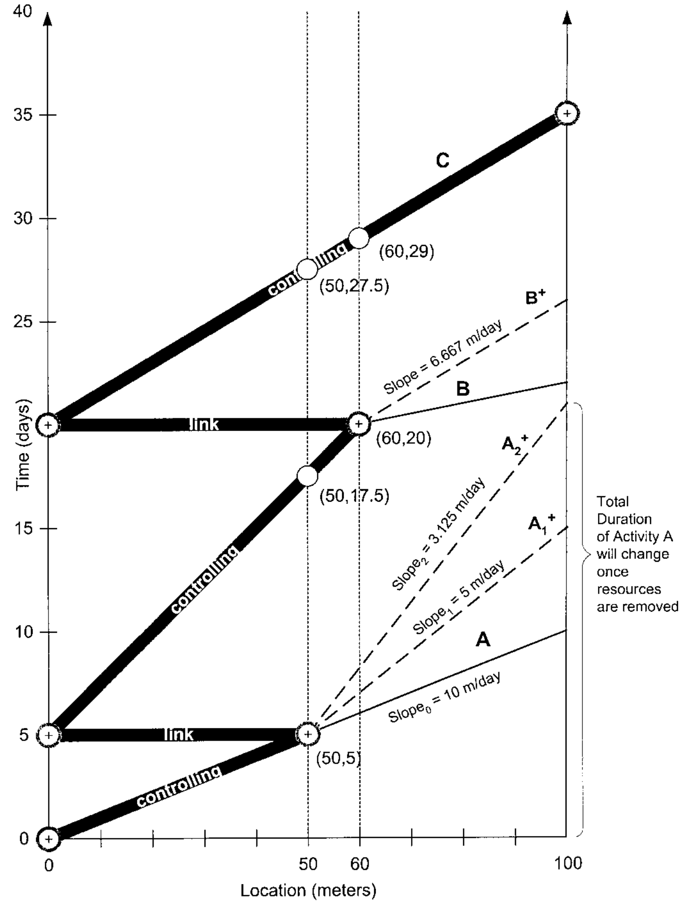


FIG. 10. Resource Management Effects and Possibilities in LSM

TABLE 2. Comparison of Critical Path Method (CPM) and Linear Scheduling Method (LSM) along Important Project Management Attributes

Attribute/dimension	CPM	LSM
Aid in reduction of uncertainty/risk	Although CPM schedules use fixed duration for activities, it can be easily complemented by PERT with statistical capabilities. This feature helps planners to get a better idea of time and schedule risks.	There is no formal method developed to date that could allow LSM to determine uncertainties in time completion.
Aid in improving production and economical operation	With the incorporation of resource leveling/allocation techniques, CPM schedules can improve the overall completion time and costs by affecting production (add or remove resources). Some limitations have been identified when scheduling continuous projects—difficult to maintain continuity in crew utilization.	Limited capabilities in improving production by changing resources. Easy to schedule continuity on linear projects, improving coordination and productivity.
Aid in achieving better understanding of objectives	In complex projects, CPM network can be very convoluted. This complexity makes them difficult to understand and communicate.	LSM is very easy to understand, and it can be used at every level of the construction project.
Accurate calculations	CPM allows the PM to calculate the time it would take to complete a project, and together with the PERT could provide statistical insights to this process. It is difficult to accurately determine and represent space restrictions (if any).	Location/time calculation is easily done. This is the greatest advantage of LSM over CPM when scheduling linear projects. This capability allows PM to accurately plan activities both in time and location.
Critical path	It is the main feature of the CPM, which can be done very easily.	The LSM algorithm calculates the controlling activity path (CAP) which is equivalent to the critical path, with the additional feature of location criticality.
Ease of use	Extensive computerization has made the CPM method easier to use. However, the user needs a considerable amount of training before actually being able to produce valuable information for controlling purposes.	Very intuitive and easy to understand. It can be used at all levels of the company (managers, superintendents and crew). Lack of computerization makes it difficult to use in large and complex projects.
Easy to update	The method could be difficult to update. Once several updates have been done, it becomes difficult to read. Updated schedules are usually out of date when they are finished.	Updating LSM is simple. Linear schedules can be used as as-built documents for claim purposes or for historical productivity databases.

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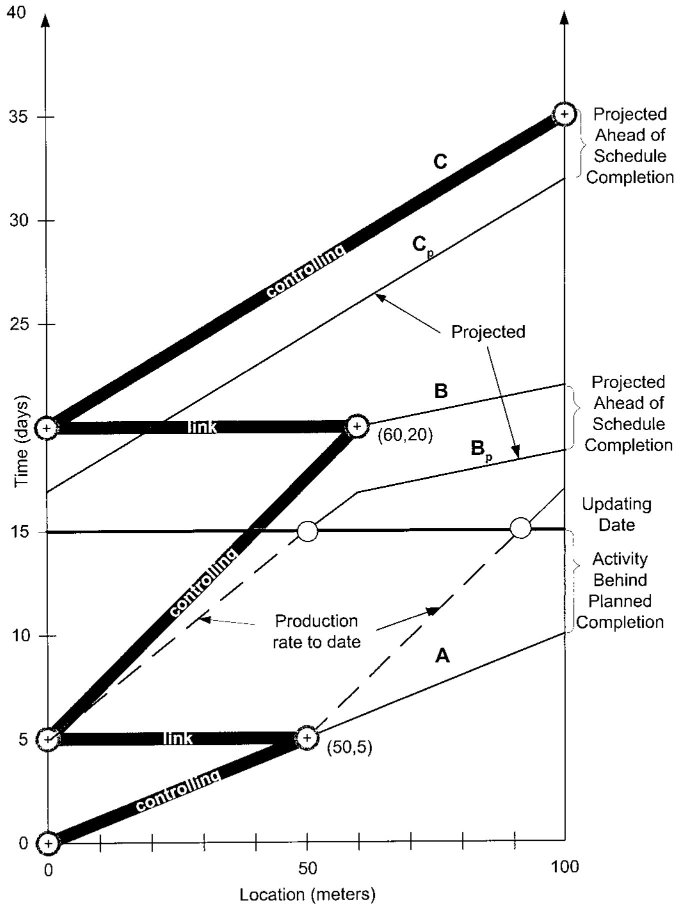

FIG. 11. Updating Schedules with LSM

scheduling tool than LSM, mainly because multiple resource management techniques and statistical analysis have been developed for it.

For the LSM to become a viable planning tool much has yet to be done in order to take the LSM to the CPM level, particularly in the resource management and duration uncertainty for LSM.

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