Challenges in Line-of-Balance Scheduling

David Arditi, M.ASCE[1]; Onur B. Tokdemir[2]; and Kangsuk Suh[3]

Abstract: The line-of-balance (LOB) method of scheduling is well suited to projects that are composed of activities of a linear and repetitive nature. The objective of this study is to set down the basic principles that can be used in the development of a computerized LOB scheduling system that overcomes the problems associated with existing systems and creates solutions to problems encountered in the implementation of repetitive-unit construction. The challenges associated with LOB scheduling include developing an algorithm that handles project acceleration efficiently and accurately, recognizing time and space dependencies, calculating LOB quantities, dealing with resource and milestone constraints, incorporating the occasional nonlinear and discrete activities, defining a radically new concept of criticalness, including the effect of the learning curve, developing an optimal strategy to reduce project duration by increasing the rate of production of selected activities, performing cost optimization, and improving the visual presentation of LOB diagrams.

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Introduction

Linear construction consists of a group of operations that involve repetitive ''units'' of construction elements. Highways, high-rise buildings, tunnels, and pipelines are good examples that exhibit repetitive characteristics where the same basic unit is repeated several times. Multiple-dwelling, multiple-floor, or linearly progressive projects allow construction to proceed in a repetitive fashion, allowing for cost and time efficiencies. To achieve these possible efficiencies, it is necessary to balance the crews. By such scheduling, a construction manager achieves continuity in the placement of all repetitive elements, thus maximizing the productivity of labor and equipment (Ashley 1980).

Network based methods such as the critical path method (CPM) are proven to be powerful scheduling and progress control tools, but are not suitable for projects of a repetitive nature, because repetitive activities often have different production rates. This phenomenon of production rate imbalance has the potential for negatively impacting project performance by causing work stoppages, inefficient utilization of allocated resources, and excessive costs (Lutz and Halpin 1992). Since there is no indication of production rates in CPM networks, this situation can never be anticipated by the scheduler during the development of a network, nor can it be detected in regular network analysis.

Bar charts, on the other hand, are simple to produce and understand and have universal appeal, but they cannot show dependencies between activities. This problem causes difficulties in modifying or updating a particular activity, which may cause additional changes in other related activities. The task of identifying which activities need to be modified or updated can accordingly be frustrating (Srigungvarl 1992).

Alternate techniques to bar charts and networks that were developed in the last 30 years are known under the generic term, ''linear scheduling methods.'' The general consensus is that linear scheduling methods are well suited to projects that are composed of activities of a repetitive nature.

Line-of-balance (LOB) is a variation of linear scheduling methods that allows the balancing of operations such that each activity is continuously performed. The major benefit of the LOB methodology is that it provides production rate and duration information in the form of an easily interpreted graphics format. The LOB plot can show at a glance what is wrong with the progress of an activity, and can detect potential future bottlenecks. Obviously, LOB allows a better grasp of a project composed of repetitive activities than any other scheduling technique, because it allows the possibility to adjust activities' rates of production. It allows a smooth and efficient flow of resources, and requires less time and effort to produce than network schedules (Arditi and Albulak 1986).

An early attempt to develop a computer application was made to schedule repetitive-unit construction by Arditi and Psarros (1987). It was limited to solving the basic LOB problem and was not designed to deal with the many implementation-related problems that were later identified. Clearly, there was a need to develop a computerized system that would make use of the principles used by Arditi and Psarros (1987) but that would also eliminate all of the associated shortcomings. A computer program that can easily and effectively be used by contractors could improve construction productivity significantly.

Since Arditi and Psarros' study in 1987, there have been several attempts to solve the various problems associated with linear

[1]Professor, Illinois Institute of Technology, Dept. of Civil and Architectural Engineering, Chicago, IL 60616. E-mail: arditi@iit.edu

[2]IT Manager, McDonough Associates, 130 East Randolph St., Suite 1000, Chicago, IL 60601-6214. E-mail: otokdemir@maiengr.com

[3]Professor, Honam Univ., Dept. of Civil Engineering, Honam, South Korea. E-mail: kssuh@honam.honam.ac.kr

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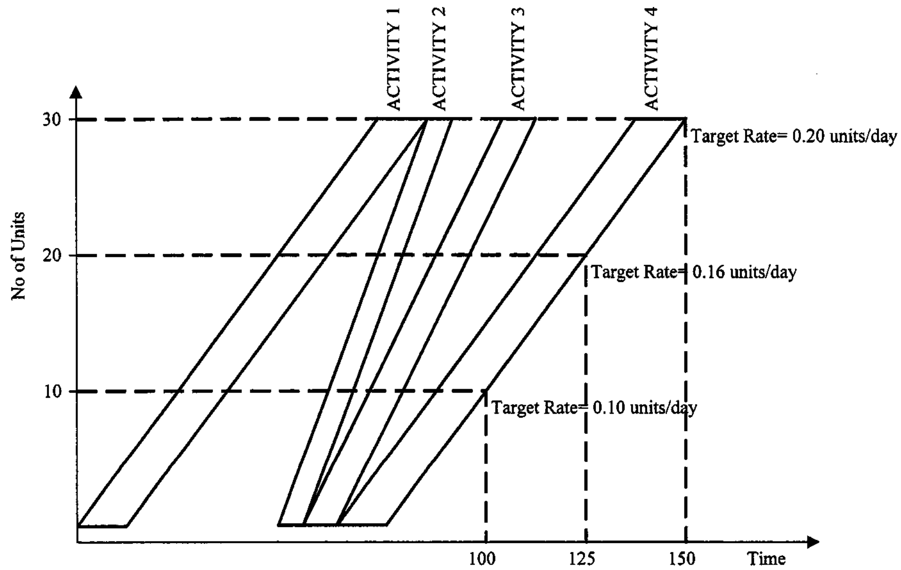

Fig. 1. Target rate in LOB diagram

scheduling. Wang and Huang (1998) introduced the multistage linear scheduling (MLS) method based on the concept of a multistage decision process. Hegazy et al. (1993) presented an effort to enhance the capabilities of linear scheduling techniques, making them more practical and more attractive for use in construction. Thabet and Beliveau (1994) described a structured procedure to incorporate vertical and horizontal constraints to schedule repetitive work in a multistory building project. Lutz et al. (1994) modeled the impact of learning in their program. Moselhi and El-Rayes (1993) studied cost optimization in association with linear scheduling. Senouci and Eldin (1996) presented a dynamic programming approach for the scheduling of nonserial linear projects with multiple nonoverlapping loop structures. Harmelink and Rowings (1998) developed a linear scheduling method that provides a level of analytical capability to the linear scheduling process. Last but not least, Harris and Ioannou (1998) created the repetitive scheduling model (RSM) that ensures continuous resource utilization. There has, however, been no systematic attempt to identify and treat all problems associated with the theory and practice of linear scheduling methods as a whole.

The objective of this study is to set down the basic principles that address the issues associated with LOB scheduling and that can be used in the development of a computerized LOB scheduling system.

Challenges in LOB Scheduling

LOB scheduling is not simple—especially when dealing with a construction project that is broken down into a large number of activities that are bound by numerous and complicated relationships and other constraints. The objective of this study includes generating a system that is easily acceptable by construction managers. The underlying principles that are extensions of the classical LOB technology can be used in developing a computer program. These principles are discussed in the following sections.

Required Date of Completion

LOB is oriented toward the required delivery of completed units and is based on knowledge of how many units must be completed on any day so that the programmed delivery of units can be achieved. Once a target rate of delivery has been established for the project, the rate of production of each and every activity is expected not to be less than this target rate of delivery (Lumsden 1968).

The optimum rate of output that a crew of optimum size will be able to produce is called the ‘‘natural rhythm’’ of the activity. Any rate of output that differs from a multiple of the natural rhythm is bound to yield some idle time for labor and equipment. That is why the System for Repetitive Unit Scheduling (SYRUS), the program developed by Psarros (1987), uses an algorithm that automatically picks the number of crews necessary in an activity such that the rate of output, a multiple of the natural rhythm, is as close to the target rate of delivery of the project as possible.

The target rate of delivery in a project is expressed in terms of the number of units to be completed per each time period (e.g., units/day, units/week, units/month, and so on). If 30 units have to be completed in 150 days, for example, a unit must be finished in not less than five days. The number of crews used in each activity is basically determined to meet this requirement of producing one unit every five days (0.20 units/day). However, the target rate of delivery cannot be easily and consistently calculated. For example, Fig. 1 illustrates that all of the activities that need to be performed to deliver 10 units can be completed in 100 days, with a rate of production of $10/100=0.10$ units/day. If one considers 10 additional units (from Unit 11 to Unit 20) where activities are performed at the same rate of production as in the first 10 units, it can be observed that 20 units can be finished in 125 days, with a rate of production of $20/125=0.16$ units/day. If one considers an additional 10 units (from Unit 21 to Unit 30), again where the activities are performed at the same rate of production as in the first 20 units, the 30 units in question will be completed in 150 days, with a rate of production, this time, of $30/150=0.20$ units/day. It appears that the simple calculation of the target rate of delivery for the project (i.e., dividing the total number of units required by the contract duration) has little meaning in determining the actual number of crews in each activity.

The practice of setting an activity's required rate of production to be equal to or faster than the target rate of delivery of the project in order to calculate the number of crews to be used in the

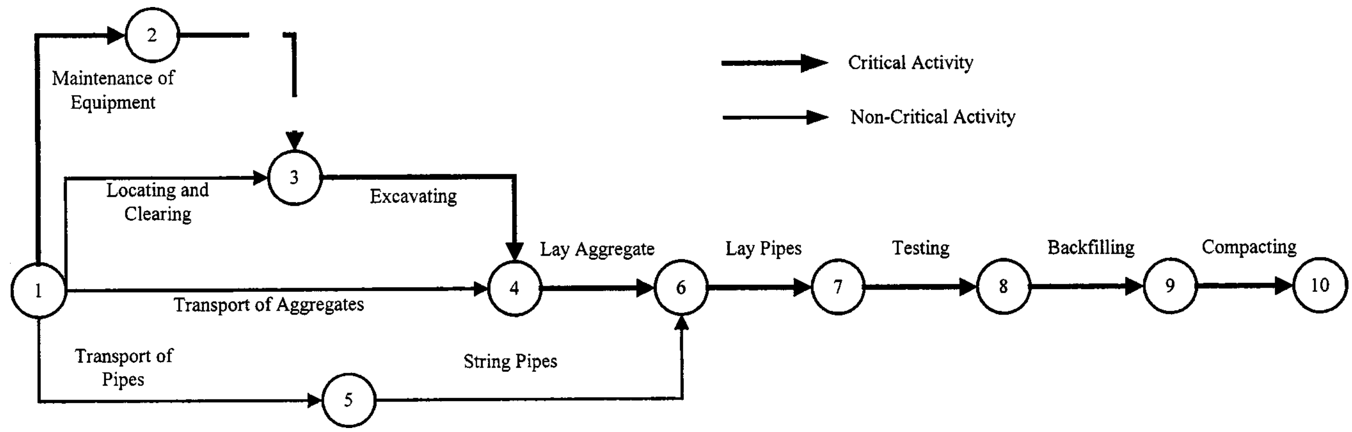

Fig. 2. Example of unit network for pipeline construction

activity has to be discontinued. A different approach is proposed to overcome this problem, where all activities start out using one crew and therefore operate with a rate of production equal to their natural rhythm. The project duration obtained after performing the LOB analysis then compared with the contract duration. If the LOB duration for the project is equal to or less than the contract duration, there is no problem. But if the LOB duration for the project turns out to be greater than the contract duration, which is the most likely outcome, then the rates of production of certain activities are increased in a given order of priority, based on resource availability and utility costs. This acceleration routine is explained in detail in a later section.

Interdependencies among Activities

LOB scheduling can be performed easily, based on a combination of network technology and the basic concept of LOB. Usually, a network diagram called the "unit network" is prepared to represent the logical sequences of individual activities in one of the many units to be produced. This unit network shows the interrelationships and/or interdependencies among activities (Fig. 2). However, organizing activities in a chronological order is not always adequate in representing interdependencies. Sometimes, special characteristics of particular activities can also have a crucial impact in defining interdependencies among activities. For example, when using the time data generated by a unit network, the use of early starts (or late starts) across the board for all activities without exception may create workflow problems. Care must be taken to make sure that network floats are not used arbitrarily or indiscriminately in the preparation of the LOB schedule. The following are two special cases that illustrate this condition.

Time Dependency

When an activity must be carried out right after the preceding activity, these two activities are characterized as activities with time dependency. In highway projects, for example, prime-coating activities should immediately follow the sweeping of the base course. Therefore, a time-dependent activity does not have the freedom to be performed at its own rate of production. Its rate of production is governed by the rate of production of its time-dependent counterpart activity.

In LOB calculations, time-dependent activities should be assigned the same rate of production in order not to provide an undesirable time gap between the two activities as the number of units increases [Fig. 3(a)]. The unified rate of production of time-dependent activities can be decided by taking the production rate of whichever of the two activities is the dominant one. The other activity whose rate of production is adjusted will inevitably suffer idle times for its crews and/or equipment, since the adjusted rate of production will cease being a multiple of its natural rhythm [Fig. 3(b)].

Space Dependency

The phenomenon of space dependency is encountered mainly in high-rise building construction. The typical example for this kind of dependency is the sequence formwork-reinforcements-concrete. These three activities have to proceed at rates of production that are very close to each other, and yet the precedence relationships have to be strictly adhered to. Otherwise, schedulers run the risk of prescribing formwork on the upper floor while the concrete on the lower floor has not been poured yet. In this case, a dependent activity does not have the freedom to be performed at its own rate of production and will have to wait until the other dependent activities within the same unit are completed. It is therefore inevitable that space-dependent activities have idle time.

In LOB calculations, the individual space-dependent activities should be considered as a combined activity whose unit duration is calculated by adding up the unit duration of each space-dependent activity. The concept is shown graphically in Fig. 4.

LOB Analysis

The early start and finish times in the first and last units should be calculated for each and every activity on all possible paths between the origin and terminal nodes of the unit network. To do this, an LOB analysis must be conducted in the following way. Once the first activity in the first unit starts at time zero, the production rate of the succeeding activity should be compared with that of the first activity. If the production rate of the first activity is faster than that of the succeeding activity, the succeeding activity in the first unit can start right after the first activity in the first unit is finished [Fig. 5(a)]. Otherwise, the succeeding activity cannot start until sufficient lead time is provided, to prevent a conflict in the logical relationship between the two activities. Therefore, the early start time of the succeeding activity of the first unit can be derived from the early start time of the succeeding activity in the last unit, which can start right after the first activity in the last unit is finished [Fig. 5(b)]. The same procedure

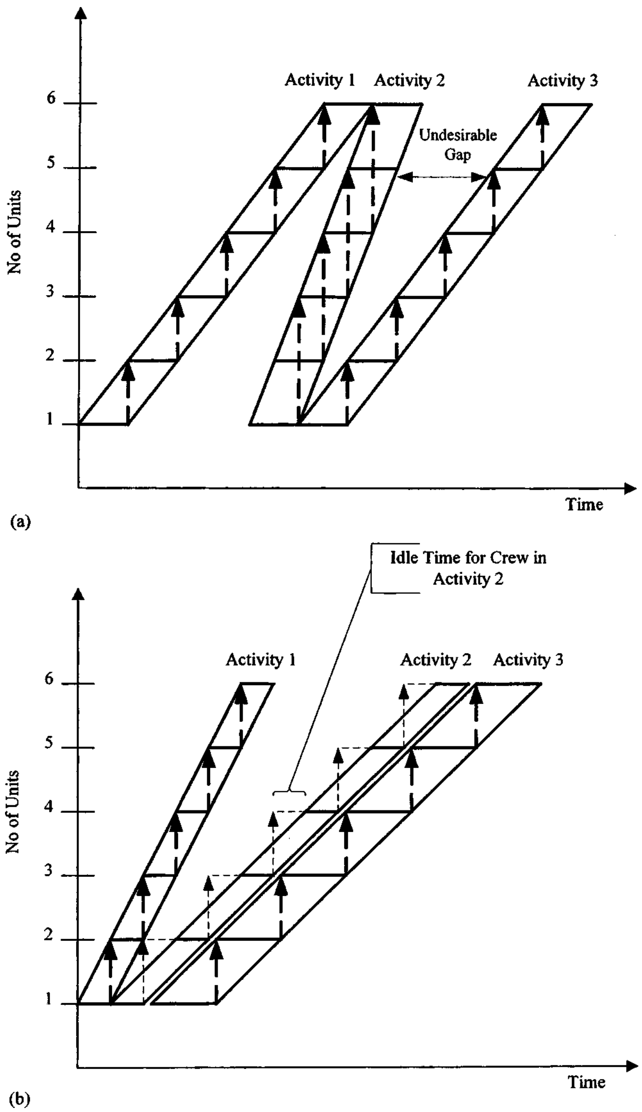

Fig. 3. Unified rate of production of time-dependent activities: (a) undesirable scheduling of time-dependent Activities 2 and 3; (b) correct scheduling of time-dependent Activities 2 and 3 (Activity 3 is dominant activity)

can be applied to all of the consecutive activities, until the early start and finish times of all activities in every path are determined in every unit.

If there is an activity that belongs to more than one path, it is called a bottleneck activity. The start time of this activity is the latest one among the early start times that are obtained by analyzing the different paths. Paths that share a bottleneck activity should be appropriately adjusted according to the bottleneck activity's start and finish times.

Dealing with Constraints

Successful scheduling should include proper sequencing of activities, comprehensive understanding of interdependent activities, and flexible linking of services that flow simultaneously. The resource requirements for each activity are to be analyzed and estimated, preferably in detail. If resources are limited, the activity start and finish times and the resource-based logic may be changed because resource analysis should be performed on a time basis.

Resource Aggregation

The distribution of resources during the course of the project is of particular importance to construction managers. Not only do managers have to make sure that the resources they allocate to the activities do not exceed availabilities, but they would also want to see as smooth a distribution as possible in order to avoid the disruption of hiring and firing crews during the course of the project. The proposed approach that is borrowed from Lumsden's (1968) work allows for the generation of resource histograms superimposed on LOB diagrams. The resource distribution for a single activity is presented in Fig. 6. The area under the histogram represents the man-hours (or equipment hours) necessary to perform that activity. It should be possible to combine distributions plotted for individual activities that make use of the same type of resource and plot a single histogram that shows the distribution of that particular type of resource over the life of the project.

Resource Limitations

To produce a realistic schedule, it is necessary to incorporate into the system a procedure that can handle resource constraints that may exist in some activities. In that respect, the activities that are performed by the same crew or equipment should be identified. Those activities cannot be carried out simultaneously because of their exclusive use of the same crew or equipment. The LOB analysis should be modified when determining the start and finish times of these activities. Regardless of rates of production, the start time of such an activity in the first unit should be determined by calculating the finish time of the preceding activity (that makes use of the same resources) in the last unit. Fig. 7 illustrates the concept of the modified LOB analysis. As can be seen in Fig. 7(b), the crew used in Activity 2 finishes its job in the last unit and then is transferred to the first unit to perform Activity 3.

Other solutions to this problem exist. For example, it should be possible for this crew to perform Activity 2 in the first few units, then perform Activity 3 in the same few units, then shift to Activity 2 to finish off the remaining units, and finally perform Activity 3 in the remaining units. Because there are no time or cost implications associated with these solutions, the merits of each alternative solution can be discussed from the point of view of logistics and the movements of the crews on the construction site.

Contractual Milestones

In addition to limited resources, contractual milestones can be important parameters to be considered in scheduling a project using the LOB technique. If the completion date of a particular activity and/or of a particular unit is specified in the contract, this information should be taken into consideration in LOB calculations. Since the target rate of a project has little meaning in LOB calculations, scheduling capabilities that can meet the requirements of partial delivery are essential.

The proposed procedure of incorporating milestones in LOB calculations makes use of an optimization process that compresses activities. Once an optimized schedule is obtained that satisfies the contract duration, the calculated date of the milestone activity is compared with the required milestone on the specified unit. If any compression is required, the production rates of relevant activities preceding the milestone activity are accelerated until the requirement is met. The activities succeeding the milestone activity are not considered in the optimization process.

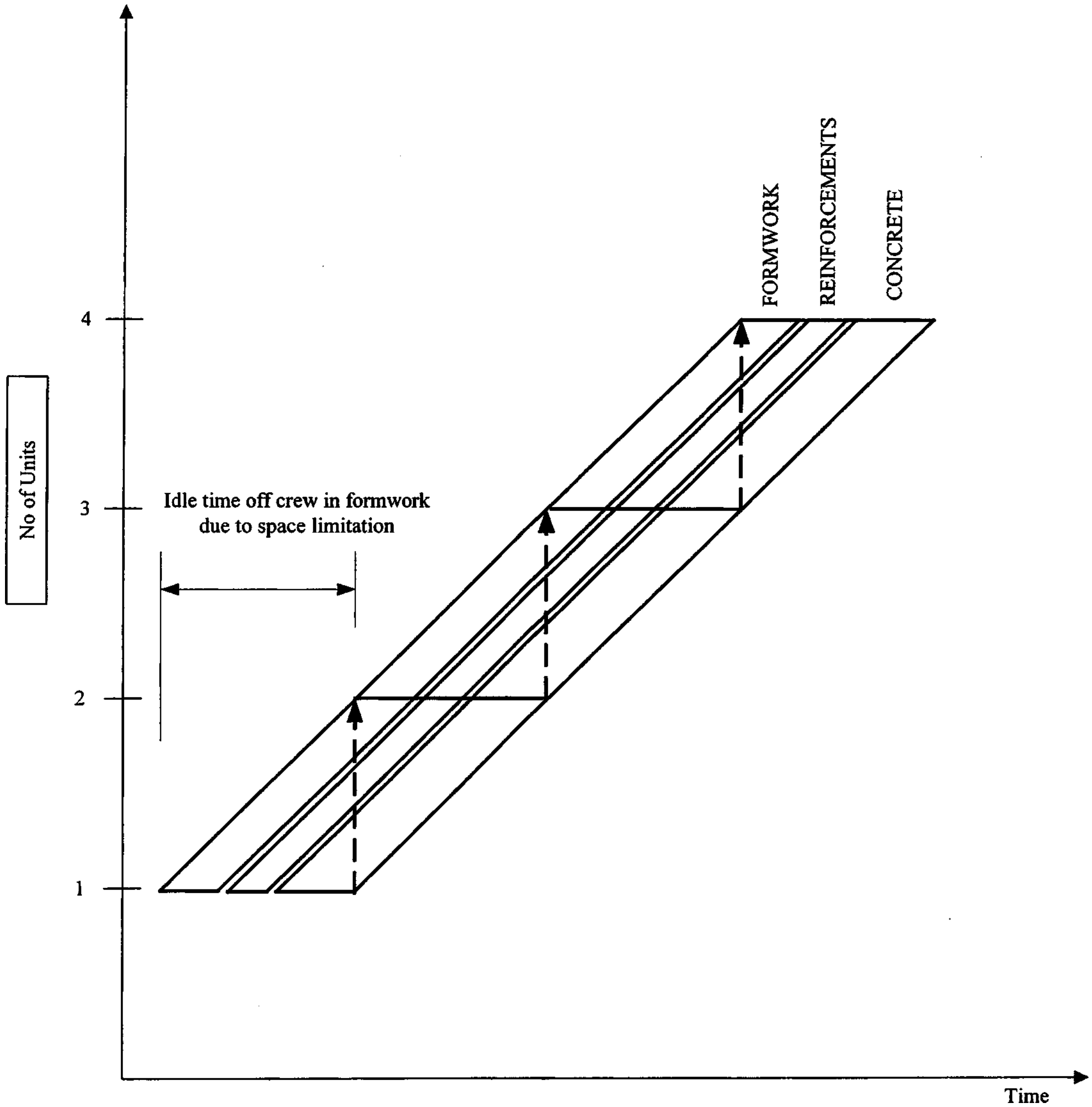

Fig. 4. Combined rate of production for space-dependent activities

Nonlinear and Discrete Activities

Linear construction, even though it is characterized as a project of repetitive nature, may contain some nonlinear and nonrepetitive activities. A nonlinear activity is characterized by repetitive operations where the output of operations is not uniform at every unit. For example, in a highway project, earthwork will vary from section to section, simply due to differences in the terrain. A discrete (or nonrepetitive) activity, on the other hand, is a one-off activity that does not repeat itself in every unit. An example of a discrete activity in a highway pavement project is the posting of the occasional sign structure.

The nonlinear activities cannot be treated like the linear and repetitive activities in LOB calculations because the outputs in these activities differ from unit to unit. The discrete portions of the project cannot be scheduled directly by the LOB method either, because these activities are not included in the unit network. Yet, both nonlinear and discrete activities may interfere with the scheduling of adjacent activities and, consequently, with the critical path. Therefore, the schedule of the entire project cannot be produced until these nonlinear and discrete activities are scheduled and coordinated with the linear and repetitive activities. There should therefore be a mechanism that allows the scheduler to accommodate nonlinear and discrete activities in an LOB schedule.

It is proposed that the actual output of a nonlinear activity be incorporated into LOB calculations on a unit-by-unit basis (Fig. 8); this is a time-consuming and tedious process, but it is justifiable, since this type of activity is seldom encountered in projects of a repetitive nature. Similarly, discrete activities, which also occur very infrequently in repetitive projects, can be handled by inserting them directly into the final LOB diagram, based on their precedence relationships.

Concept of "Criticalness"

Producing and using only a unit network instead of developing an overall network or an LOB schedule for the entire project is not a reliable solution in repetitive jobs. If only the unit network is used for scheduling and control purposes, the scheduler cannot realize that noncritical activities may become critical after certain units are completed and may disrupt the rate of production at which

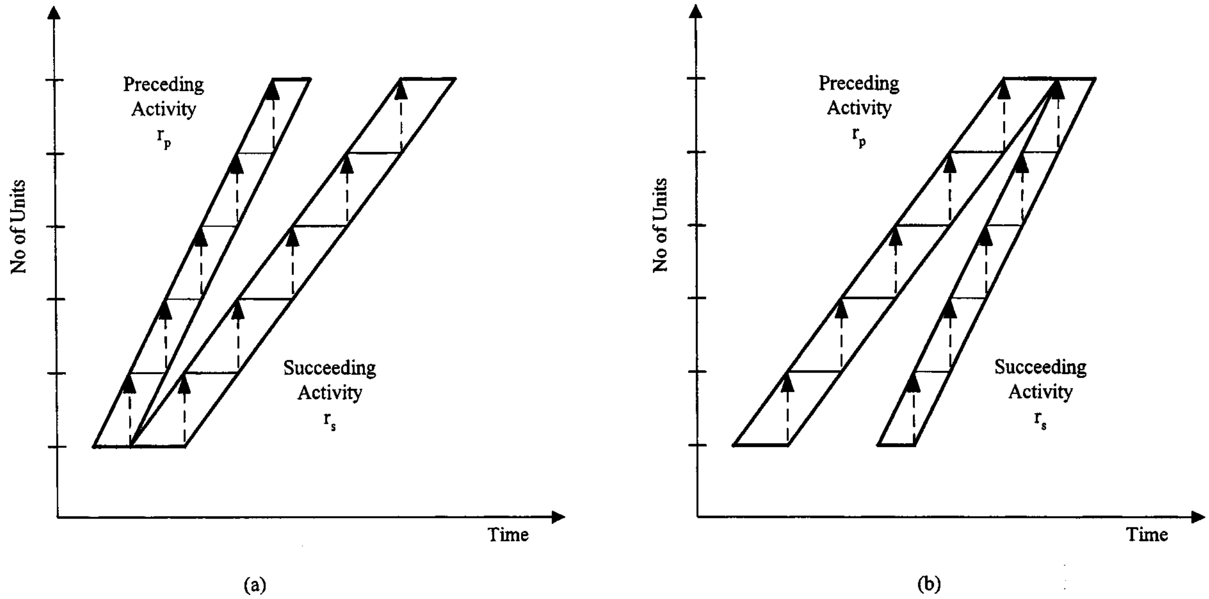

Fig. 5. LOB analysis: (a) $r_p > r_s$; (b) $r_p < r_s$

succeeding activities are performed. Care must be taken to determine critical activities in repetitive unit construction. Critical activities in the unit network schedule may not coincide with critical activities in an LOB schedule, because in LOB, the production rate is the major parameter that determines criticalness, whereas in a network, only activity durations are used for this purpose.

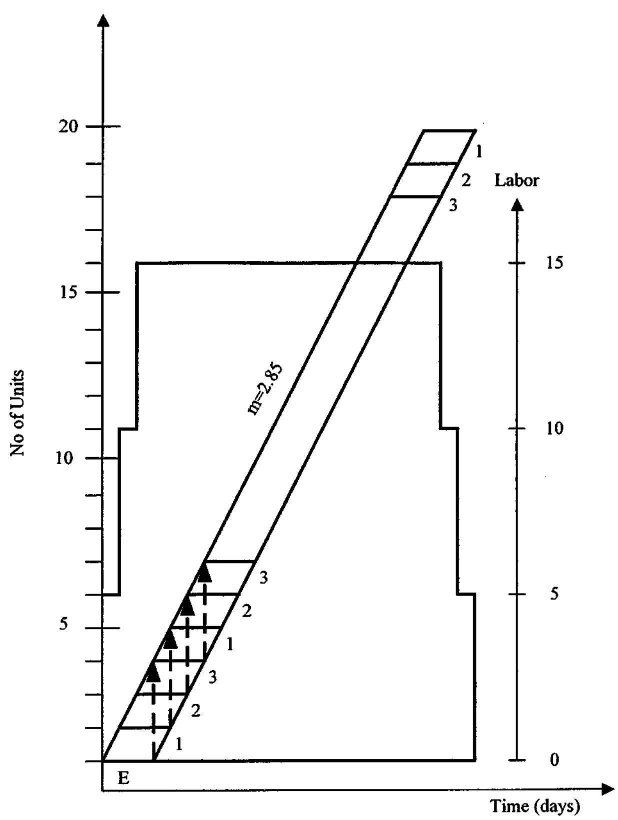

Fig. 6. Resource histogram for one LOB activity

The concept of criticalness in LOB is different from the concept of criticalness in networks. Harmelink and Rowings (1998) successfully prove this argument by identifying the "controlling activity path" through a linear schedule. But most existing LOB technologies do not recognize this difference—nor do they define criticalness and floats in LOB terms. Since these concepts form the basis of "management by exception," it is important that an LOB algorithm be equipped with a routine that could single out critical and near-critical activities for intense and high-priority management action, and floats to allow for flexibility if necessary. Floats must therefore be carefully calculated in the LOB schedule, as they would be in network scheduling.

A unit network is used to identify the logical relationships among activities in one of the many units to be produced. There is at least one critical path in a unit network that is identified by analyzing the network. Typically, critical activities are treated as important parameters in determining the project schedule because no floats are available in these activities. However, in LOB calculations, continuous use of labor and equipment should be maintained in each activity to achieve efficient performance.

Due to the different production rates of project activities, the critical activities identified after an LOB analysis may or may not coincide with the critical activities identified after analyzing the unit network. For example, whereas the activities that lie on Path 1-2-3-4-6-7-8-9-10 are found to be critical in the unit network of the pipeline project presented in Fig. 3, the LOB analysis of the same project indicates that it is the activities on Path 1-5-6-7-8-9-10 that are critical in the context of the overall project (Fig. 9). In the proposed LOB calculations, all paths are identified from the first node to the last node in the unit network. The precedence relationships in all paths of activities in series are used in the LOB analysis, but it is the production rate that is the major parameter that determines criticalness.

The critical path identified in the LOB analysis may become noncritical if the production rate of an individual activity is changed by adjusting the number of crews employed in the activity or by altering its constraints. Therefore, for a thorough LOB

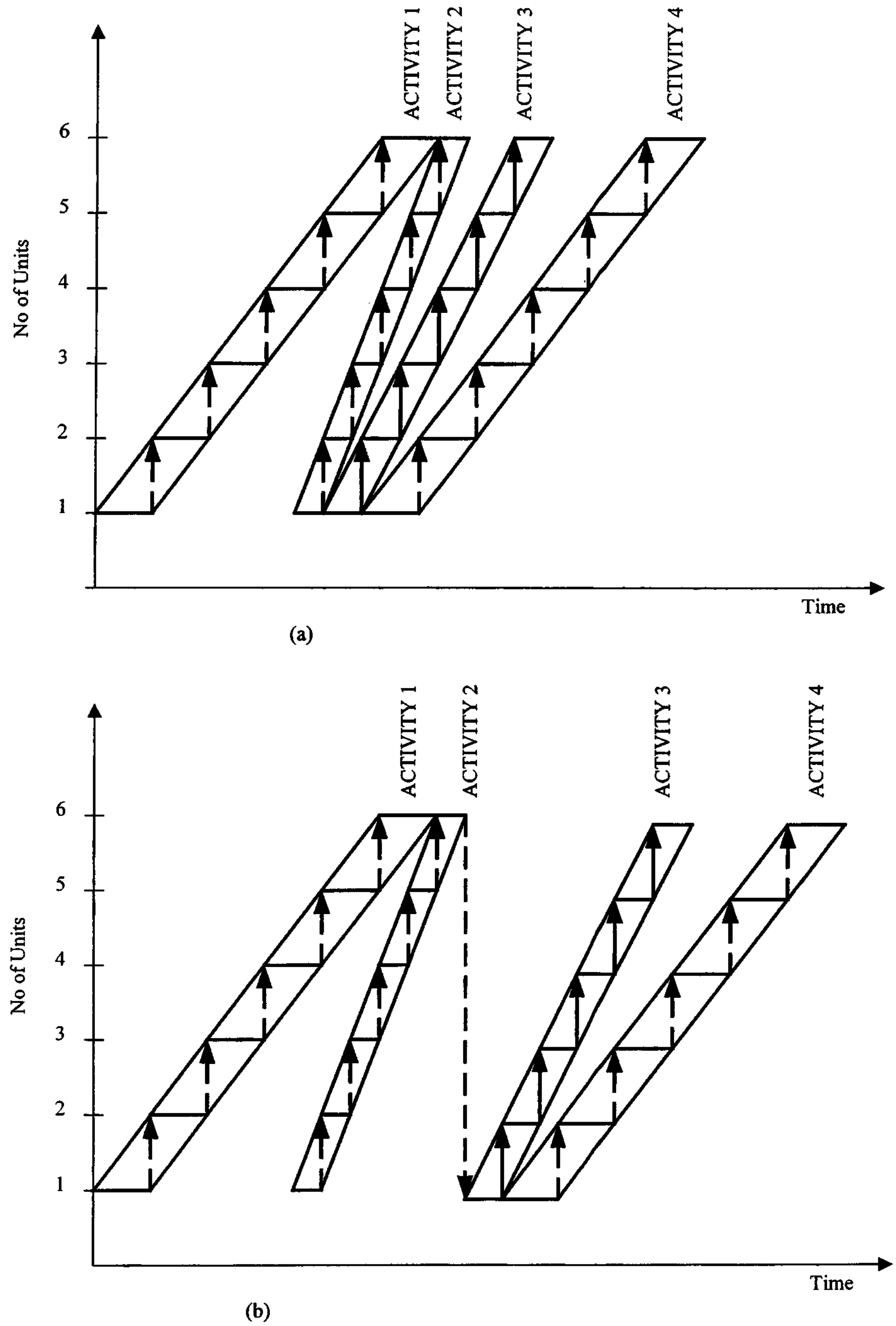

Fig. 7. LOB schedule with resource limitations: (a) activities performed by separate crews; (b) Activities 2 and 3 performed by same crew

analysis, a record should be kept of all serial paths representing all logical sequences in a unit network.

Learning Curve Effect

The LOB scheduling technique makes the basic assumption that the relationship between time and the number of units produced is linear (i.e., constant rate of production over time). In reality, it is not so, because the more times an operation is performed, the shorter will be the time needed to perform it. This phenomenon is called the learning curve effect. The time spent for the performance of the same operation decreases precipitously in the first few units and tapers off after a certain number of repetitions. The effect of the learning process is not considered in the traditionally linear relationship between time and the number of units produced, but in the ideal situation it should be incorporated into a schedule of repetitive-unit construction in order to reflect the real conditions (Arditi et al. 1999).

The learning phenomenon cannot be directly reflected in the LOB method because the LOB method, in its existing form, requires that the rate of production of each activity be kept constant during repetitive unit construction. To incorporate effects of learning into the LOB method, the learning rate of each activity should be established and then converted into man-hour estimates. The activity durations in each unit from the first to the last now have to be computed separately because the rate of production of each activity is no longer constant. The resulting production curves denoting the start and finish times, respectively, of each activity

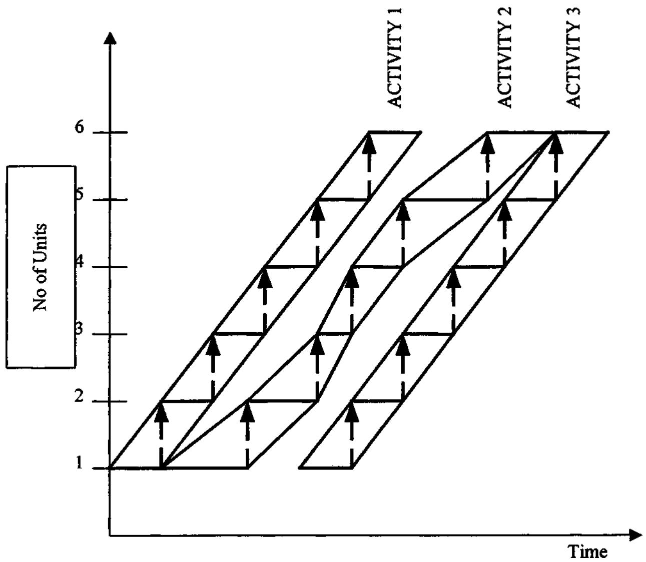

Fig. 8. Incorporating nonlinear activity (Activity 2)

plotted in an LOB diagram are neither linear nor parallel anymore. Arditi et al. (1999) used fuzzy set theory to develop production rules to treat both factual and uncertain information in the formulation of a learning model that was used to generate the LOB diagram presented in Fig. 10. The sudden change in the slope of an activity in Fig. 10 indicates a reduction in the number of crews used in that particular activity; indeed, as learning pushes productivity up, less manpower is needed to perform the same activity.

Optimum Crew Size

A crew of optimum size is defined as a combination of trade workers, materials, and equipment that usually guarantees maximum productivity in an activity. This crew is expected to carry out the related activity in the most cost-efficient way.

Regardless of productivity issues, there are several ways that may be considered in effort to increase the production rate of an activity so as to meet the requirement of the project completion date. Scheduled overtime, multiple shifts, and overmanning may be considered in this respect.

A study cited by The Business Roundtable (Scheduled 1980) concludes that four weeks of 8 h/day was found to be 16% more efficient than four weeks of 9 h/day. This study was based on the total cost of finished products manufactured by an identical process under two different "hours per day" of work time. Longer working hours caused a reduction in effectiveness due to fatigue, which in turn reduced the productive output of labor considerably. On extended overtime, the reduced productivity of workers for a week's work is equal to or greater than the number of overtime hours worked. The premium cost for overtime hours, plus the loss in productivity for the total hours worked, results in an unreasonable inflation of the unit labor cost.

Using multiple shifts is another alternative that can increase the rate of production. Second-shift work is more productive than scheduled overtime. However, it requires tremendous effort on the part of management. Lighting, engineering support, and supervision should be provided for the second shift. In addition, it is very difficult to transfer work from the first shift to the second shift and from the second shift to the first shift, and so on.

Overmanning is the worst alternative that can be used to expedite the completion time of an activity. The manning level is a key factor in labor productivity. Crowded work areas and improper combinations of trade workers may create crew interference and, in turn, may cause productivity to slow down severely. Several technical reports provide inefficiency curves for overmanning. According to Borcherding (1989), firms report that an activity that is overmanned above normal scheduled crew sizes can suffer drops in productivity that range from 15 to 32%.

None of the previously mentioned alternatives are cost-effective ways of increasing activity production rates. An optimum schedule can therefore be achieved by strictly adhering to the use of one or more crews of optimum size in the calculation of the rate of production of each activity. In case the production rate of an activity that uses one crew of optimum size has to be increased in order to complete the project on time, additional crews are allocated as long as they are available.

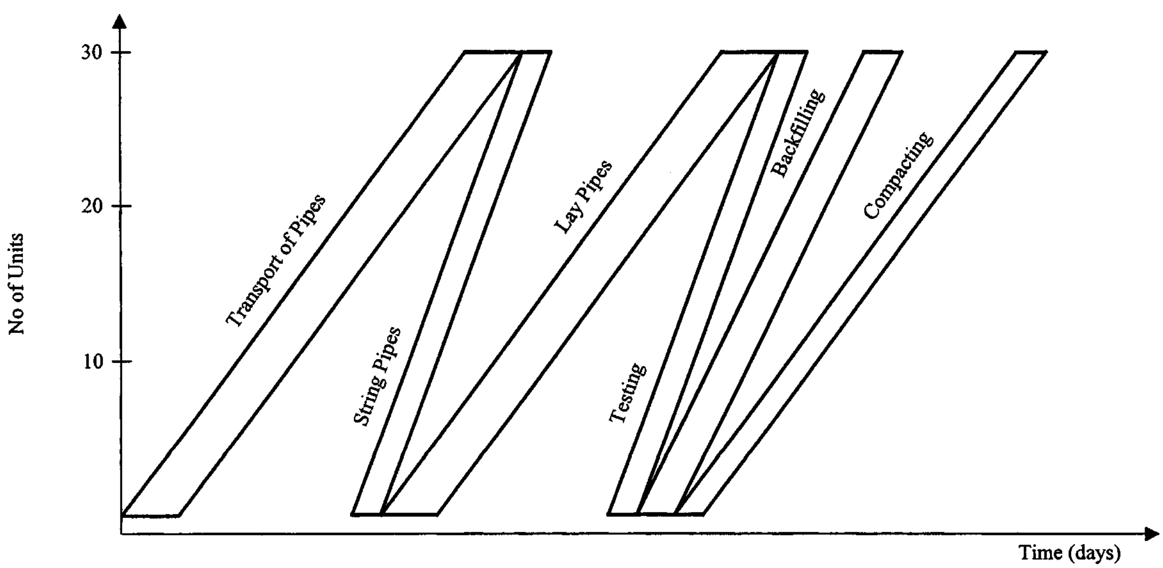

Fig. 9. Critical path in LOB schedule

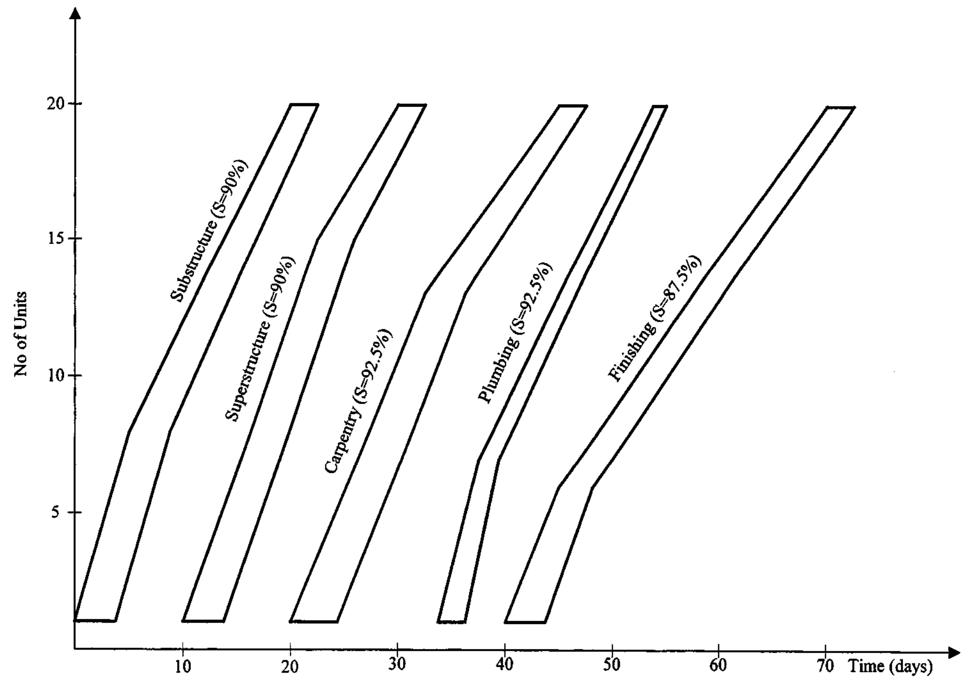

Fig. 10. Line-of-balance scheduling with learning

Estimates of man-hours and optimum crew sizes are obtained from field personnel, technical specifications, and previous records. The activity durations thus calculated diverge sometimes from the performance actually achieved on-site, and have to be corrected to better reflect actual conditions. One of the adverse characteristics of the LOB method is that the error introduced when estimating the production rates of activities, even if minimal, will be magnified into significantly large deviations because differences between actual and estimated rates of production in individual activities compound as repetition increases (Fig. 11). This extreme sensitivity of the LOB method to estimation errors must be well recognized at the outset, and thus can be rectified by simulating different situations several times with different man-hour requirements.

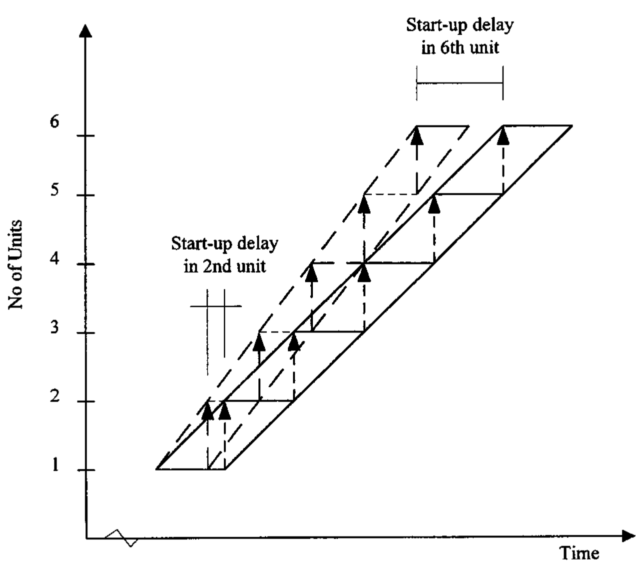

Fig. 11. Effect on activity start-up times of error in estimated activity duration

Acceleration Routine

In the last unit of the project, the finish time of the last activity on the critical path indicates the total project duration. The project duration obtained in the first run of the proposed system is the minimum project duration obtained with only one crew used per activity. In most cases, this project duration will exceed the required project completion time. The production rates of selected activities have to be increased in order to reduce the total project duration to the level specified by the contract.

It is assumed that the only way to accelerate production without increasing cost is to increase the number of crews. Other alternatives including overtime, more equipment, and expanded crew size increase the direct cost of an activity because, as discussed in the previous section, only the optimum crew size can achieve maximum productivity in an activity. Alternatives such as using faster and more efficient equipment and more sophisticated construction methods could accelerate production, but may often be impossible in practice; had a company been in possession of more productive equipment or more advanced construction know-how, it would have used these resources in the first place.

Cost optimization can therefore be achieved by using a multiple of the natural rhythm of the activity because the natural rhythm of the activity is the optimum rate of output that a crew of optimum size can produce. Once the number of crews used in an activity, and by implication its rate of production, is established, it should remain constant throughout the completion of the entire project in order to take advantage of the continuity in the labor force, unless the learning effect requires the disbanding of some crews ahead of project completion. Using partial crews and adjusting production rates up and down during the course of the

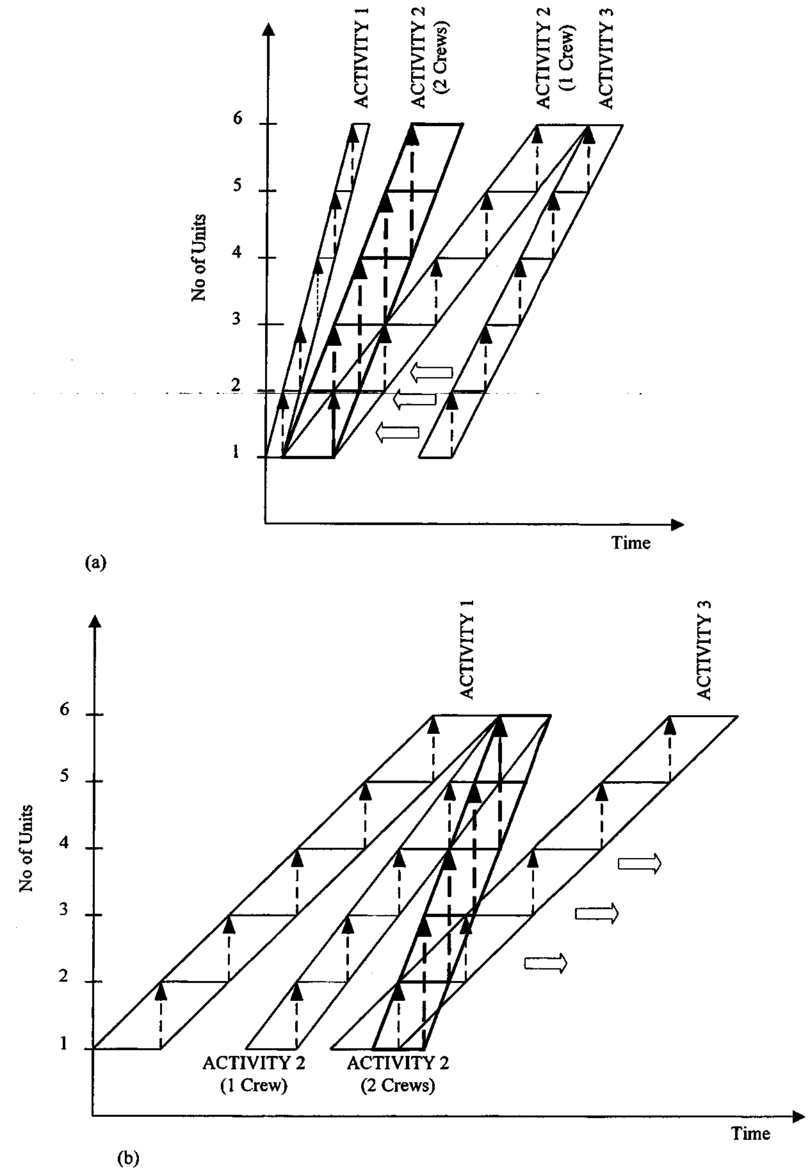

Fig. 12. Effects of increased rate of production on Activity 3: (a) Increasing the production rate of Activity 2 will allow Activity 3 to start and finish earlier; (b) increasing the production rate of Activity 2 will delay the start and finish of Activity 3

project by changing the number of crews may increase costs due to the associated disruption.

In the proposed compression analysis, activities on the critical path of the LOB schedule are compressed in order to meet the required completion date. A priority system that selects the activities to be accelerated is established to perform cost-effective compressions. The number of available crews is the first priority in this selection. If an additional crew is not available, there is no physical way to accelerate the activity. The rates of production of activities constitute the second priority in the selection process. Since the rates of production of activities are first calculated based on only one crew of optimum size, the activity with the longer unit duration has a slower rate of production, which in turn means a higher potential to compress the overall project duration. Once the activity with the longest unit duration is identified, it is compressed by adding a second crew, which doubles its rate of production; in the next iteration, the total duration (over the totality of the units) of this activity drops to half of its original duration.

Another reason why an activity with the longest unit duration (and therefore the lowest production rate) must be compressed first is because increasing the production rate of an activity with a shorter unit duration (and therefore a higher production rate) may delay the start time of the succeeding activity and, in turn, increase the total duration of the project. Figs. 12(a and b) illustrate this phenomenon. Fig. 12(a) shows that increasing the rate of production of Activity 2 (which has the longest duration and therefore the flattest production slope) would enable Activity 3 to start earlier, in this way reducing the total project duration. On the other hand, in Fig. 12(b), increasing the rate of production of Activity 2 (which does not have the longest duration and the flattest production slope) delays the start time of Activity 3 and ends up increasing the total project duration. Compression analysis of an LOB schedule should take these possible conditions into consideration before increasing the number of crews/amount of equipment in a particular activity.

An estimated rate of project progress is often required by contract-letting agencies in the form of a progress curve (percent

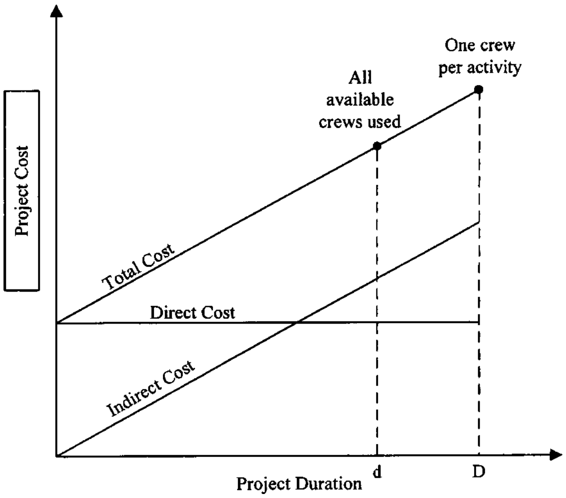

Fig. 13. Cost optimization with LOB

of cost). In bar-chart development, the percent monthly progress on each activity is often estimated by the scheduler, based on judgment and the classical S-shaped activity time-progress curve. Progress control by LOB becomes quite efficient, especially when it is used in association with cost data.

Cost Optimization

Most available scheduling techniques based on the LOB concept have been developed to reduce project duration with little or no regard for project cost. Given the concept of the optimum crew size and the natural rhythm, the cost optimization issue, i.e., finding the shortest project duration for the least total production cost, becomes obvious; the shortest project duration corresponds to the least cost solution. This can be explained by the utility relationship between direct cost and activity duration. This relationship is linear because, as explained in the preceding section, an activity's duration can be reduced only in direct proportion to increasing the number of crews working on it, with each crew working in a different unit and not interfering with each other. Indeed, as observed in Fig. 13, there is no difference in direct costs between a project that uses, say, one crew per activity and the same project that uses as many crews in activities as are available.

It can also be observed in Fig. 13 that the indirect cost decreases with shorter project duration. It can therefore be concluded that the shortest possible project duration is always the most economical solution (i.e., lowest direct+indirect cost), assuming that optimum-size crews are used on all activities and that there are no cash flow constraints.

Visual Presentation of LOB Diagram

The degree of the detail of the LOB diagram must be carefully evaluated. If too many activities are plotted, the diagram becomes a jungle of oblique lines that also sometimes cross each other. An alternative is proposed that displays the LOB diagram of each individual path, one path at a time. The use of color-filled lines as well as vertical and horizontal lines showing the movement of the crews can also help. An experienced scheduler can select an optimum level of detail.

A major difficulty in preparing the LOB diagram lies in plotting overlapping activities that have the same rate of production. For example, if two consecutive activities are overlapping, it is difficult to differentiate between them unless they are indicated by colored lines. The choice of the appropriate scale is also critical for better understanding and for communicating the information contained in an LOB schedule. It has been observed that foremen and subcontractors are more receptive to LOB diagrams than to arrow network diagrams, but are not receptive enough to use them in lieu of bar charts (Arditi and Albulak 1986). The LOB schedule has to be converted into weekly bar charts where critical activities and floats are clearly marked.

Conclusion

Several issues associated with LOB applications have been identified in this study. The objective of this study includes generating proposals that address these issues in order to generate a computerized system that is easily acceptable to construction managers. The following are proposed:

1. A new approach is proposed that allows for the handling of logical and strategic limitations associated with the characteristics of repetitive activities. This approach is expected to increase the accuracy and the efficiency of current LOB analysis.
2. "Learning" is a phenomenon that can play an important part in determining performance in certain activities. It is proposed that it should be factored into LOB calculations.
3. An algorithm that performs project acceleration is proposed that can add a great deal to the value of an LOB scheduling system and that can help in optimizing total project cost.
4. Nonlinear and discrete activities are sometimes encountered in repetitive projects. An approach is proposed that allows for the handling of these activities by an LOB scheduling system without disrupting the underlying philosophy.
5. Various alternatives are proposed, including generating LOB diagrams of individual paths and converting LOB information into bar charts, that can help alleviate visual problems of presentation if the system is to be widely accepted by schedulers and managers.

There is evidence that linear construction has a repetitive nature that does not allow the efficient use of bar charts and network methods, because bar charts and networks sometimes generate inaccurate and misleading information in repetitive situations. Hence, there is a need for more powerful methods of scheduling that will allow the user to make optimum use of time and resources, run the project efficiently, and monitor progress effectively. A computerized system that addresses the issues discussed in this study could be of great value to managers of repetitive construction.

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