Practical limitations of line-of-balance in scheduling repetitive construction units

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Although Line-Of-Balance (LOB) scheduling can be superior to Critical Path Method (CPM) in repetitive-unit construction, there are practical indications that its use is not widespread. In this research, the major limitations of LOB methodology are identified. A tool of handling logical and strategic limitations, caused by the particular characteristics, to construct repetitive units is provided. The schedule of repetitive construction units should be satisfying the following constraints: logical sequence, crew work continuity, number of employed crews, work crew size, project resources, work progress rate, workflow direction, contractual milestones, learning phenomenon, in addition to nonlinear and discrete construction process. These constraints with underlying principles are briefly discussed.

بالرغم من أن طريقة خط التوازن تعتبر أعظم نفعا من طريقة المسار الحرج في التخطيط الزمني لوحدات التشييد المتكررة، إلا انه هناك دلالات عملية تشير إلي عدم اتساع انتشار استخدامها. في هذا البحث تم تحديد أوجه القصور الرئيسية في طريقة خط التوازن القائمة حاليا، و ذلك بمعالجة الحدود المنطقية و الاستراتيجية الناجمة عن الخصائص العملية لتشييد الوحدات المتكررة. أن التخطيط الزمني لتشييد الوحدات المتكررة يجب أن يحقق القيود التالية: التتابع المنطقي، استمرارية العمل، عدد أطقم العمل، حجم طاقم العمل، موارد المشروع، معدل تقدم العمل، اتجاه تدفق العمل، الأهداف المرحلية لعقد المقاولة، بالإضافة إلي ظاهرة التعلم، وقد تم مناقشة هذه القيود بمفاهيمها الضمنية بإيجاز.

Keywords: Database keywords, Construction management, Repetitive construction, Line of balance, Scheduling techniques

1. Introduction

Repeating units are commonly found in construction industry such as typical floors in multistory buildings, houses in housing developments, stations in highways, pile-driving, production of pre-cast concrete units, meters in pipelines network, long bridges, tunnels, railways, airport runways, or water and sewer mains. These construction projects are characterized by repeating activities, which in most instances arise from the supervision of a generalized activity into specific activities associated with particular units.

Construction crews assigned to repeating activities often perform the work sequentially. The assigned crews repeat the same task in a number of repetitive units in the construction project, moving from one repetitive unit in the project to the next. Because of this frequent crew movement, construction of repetitive activities should be scheduled in such a way as to enable prompt movement of crews among the repetitive units, 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 [1].

Successful scheduling should include proper sequencing of construction activities and understanding of interdependent activities. The resource requirements for each activity are to be analyzed and estimated, preferably in detail. If project resources are limited, the activity times and the resource-based logic may be changed because of time base analysis of resources. Unlike traditional scheduling techniques, Line-Of-Balance (LOB) accounts directly for crew work continuity as well as resource availability to facilitate effective resource utilization.

2. LOB weakness

Kavanagh [2] indicated that the LOB

techniques were designed to model simple repetitive production processes and, therefore, do not transplant readily into a complex and capricious construction environment.

Arditi et al. [3] commented about the visual problems with the presentation of the LOB diagram, and recommended color graphics to differentiate between overlapping activities.

Neale et al. [4] tried to refine the LOB in a spreadsheet format by introducing activities that run concurrently. They confronted the complex relationships that their spreadsheet had to express and concluded that it was practically meaningless to draw the output in the form of a diagram with an incomprehensible mass of flow lines.

Neale et al. [5] mentioned that LOB could show clearly only a limited amount of information and a limited degree of complexity, especially when using the technique to monitor progress.

Al Sarraj [6] gave a review of previous researches revealed that the LOB method was not formalized in acceptable form for general implementation, so its use in construction industry has been very limited and no attention have been made for its computerization.

Several constraints are considered in the present research to define the scheduling cases and to formalize the scheduling decisions to sequence each activity. As such, resource-driven scheduling of repetitive activities required the satisfaction of the following constraints: (i) logical sequence; (ii) crew work continuity; (iii) number of employed crews; (iv) work crew size; (v) project resources; (vi) work progress rate; (vii) workflow direction; (viii) contractual milestones; (ix) learning phenomenon, and (x) nonlinear and discrete construction process.

3. Logical sequence

Scheduling construction projects with repeating activities are performed 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 sequence of individual activities in one of the many units to be produced. This unit network shows the interrelationships and/or interdependencies among activities. The precedence relationships define the logical sequence between successive construction activities, in compliance with the construction methods used. All types of logical precedence relationships between succeeding activities (start-to-start; start-to-finish; finish-to-finish; and finish-to-start) can be represented in the unit network.

Yi et al. [7] developed a scheduling method to model and schedule repetitive construction projects, this method is not network based so the objective of this research is to develop networks for repetitive unit projects. The first step in this method is to graph activities in a two dimensional form, the horizontal axis represents the number of crews to be used for each activity and the vertical axis represents the repetitive section or unit. The second step in developing the network is to optimize the activity arrangement to minimize by re-linking the activities according to the earliest finish time. The advantage of this method is it can help inexperienced schedulers in creating a network for repetitive construction projects. In addition, the developed method can be automated using spreadsheet programs.

However, organizing construction activities in a sequential order is not always adequate in representing interdependencies. Sometimes, special characteristics of particular activities can also have an impact in defining interdependencies among activities. Especially, 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. Time and space dependency are two special cases that illustrate this condition.

3.1. Time dependency

When a construction activity must be carried out right after the preceding activity, these two activities are characterized as activities with time dependency. In highway projects, 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 production rate is governed by the rate of production of its time dependent counterpart activity.

In LOB calculations, time-dependent activities should be assigned to the same rate of production in order not to provide an undesirable time buffer between the two activities as the number of units increased, fig. 1.

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 production rate will cease being a multiple of its natural rhythm, fig. 2.

3.2. Space dependency

Thabet el al. [8] focused on the workspace constraints that can be caused during execution of repetitive construction units in a multistory building. Although the limited workspace problem could be an important factor in work continuity, that problem is not considered in the most referred literatures.

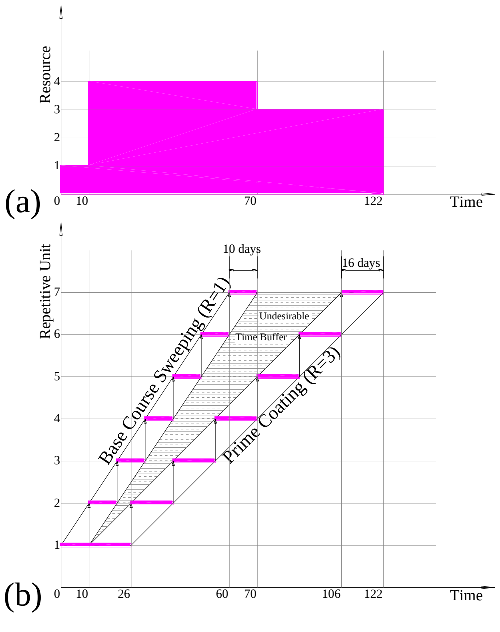

Fig. 1. Undesirable idle time between two successive activities: (a) resource histogram; (b) project schedule.

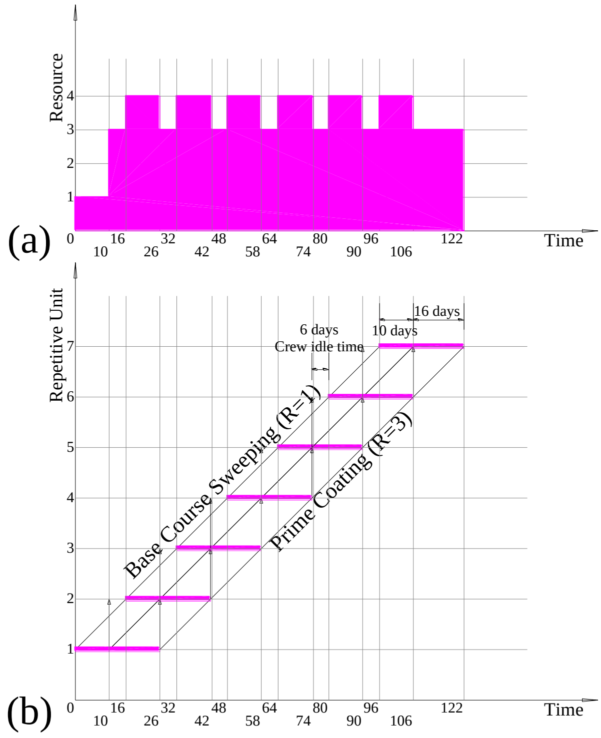

Fig. 2. Undesirable crew idle time for repetitive activity: (a) resource histogram; (b) project schedule.

The phenomenon of space dependency is encounters mainly in high-rise building construction. The typical example for this kind of dependency is the sequence formwork, reinforcements, and concrete pouring. These 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.

4. Crew work continuity

The application of such crew work continuity during scheduling of repetitive construction leads to the following managerial function: (i) Maximize the benefits from the learning curve effect for each crew. These results have considerable savings in time and cost (ii). Minimize idle waiting intervals of equipment and labor. (iii) Minimize extra effort associated with work interruptions as example: setup time, temporary storage of tools and materials [11] (iv) Minimize the off-on movement of crews on a project once work has begun.

Despite the apparent advantages of maintaining crew work continuity, its strict application may lead to a longer overall project duration in some cases. Selinger [12] suggested that the violation of the continuous work constraint, by allowing work interruptions, might reduce the overall project duration and accordingly, the project indirect cost.

Elwany et al. [13] commented that work interruptions result in idle time and, accordingly, may lead to increased direct cost. Hence, to achieve maximum time and cost savings, the splitting of certain activities should not be allowed. This is considered essential for major trades such as structural framing, block works, external cladding, Heating, Ventilation, and Air Conditioning (HVAC) ductworks.

Russell et al. [14] criticized the application of work continuity for all activities, and suggested that the work continuity condition should be satisfied but not strictly enforced in scheduling repetitive activities.

For example, a crew assigned to a construction activity in a number of repetitive units should be able to move promptly from one unit to the next immediately in order to minimize its idle time, as shown in fig. 1.

5. Number of employed crews

The crew availability constraint depends on the available number of crews that can be assigned to activity in all repetitive units of the construction project.

For example, a single crew assigned to prime coat 7 successive units fig. 1. can start work on the second unit only after finishing the first. While two crews assigned to execute the same units, fig. 3. can work simultaneously on repetitive units.

In case of a large housing project, each house is represented by one typical subnetwork. There are no logical relationships between the typical activities of the subnetworks. Traditionally, on a job site of a housing project, the main question a project manager asks is how many crews of a particular trade (or sets of roof shutters, etc) are necessary to be employed to complete the project on time?

Therefore, a planner must consider designing a schedule that is responsive to this need. In other words, making the schedule resource oriented. This understanding should encourage the planner to use resource leveling along with time scheduling, that will be presented in future research by the author.

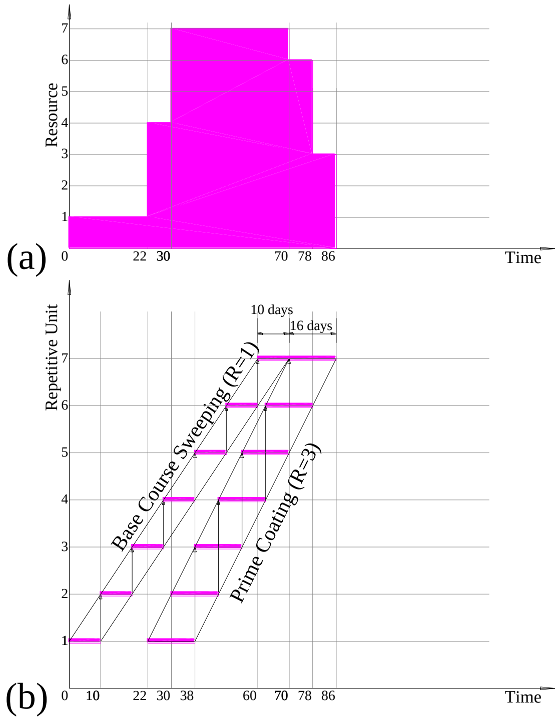

Fig. 3. Effect of employed multiple numbers of crews on repetitive activity: (a) resource histogram, (b) project schedule.

6. Work 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 (Suhail et al. [15]). This crew is expected to carry out the related activity in the most cost-efficient way.

Regardless of productivity issues, several ways may be considered in effort to increase the production rate of an activity to meet the requirement of the project completion date. In this respect, it may be considered scheduled overtime, multiple shifts, and over staffing.

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.

This extreme sensitivity of the LOB method to estimation errors must be well recognized at the outset in future work. Thus, it can be rectified by simulating different situations several times with different man-hour requirements.

7. Project resources

7.1. Resource profile

The distribution of resources during the project progress, as seen in fig. 3-a, is one of particular importance for construction managers. Not only do managers have to make sure that the resources they allocate to the activities do not exceed availabilities (as example, R<=6). Nevertheless, they would also want to see as smooth a distribution as possible [fig. 1-a], to avoid the disruption of hiring and firing crews during the project progress, fig. 2-a.

The original approach that is borrowed form Lumsden's [16] work allows for the generation of resource histograms superimposed on LOB diagrams. The area under the histogram represents the earth moving equipment hour's necessary to perform that activities. It is 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.

7.2. Resource limitations

It is necessary, from my opinion, 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 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. 4 illustrates the concept of the modified LOB analysis. As can be seen in fig. 4-b, the equipment used in “base course sweeping” is finished its job in the last unit and then is transferred to the first unit to perform “prime coating.”

Other solutions to this problem exist in details (Hafez, [17]). For example, it should be possible for this crew to perform “base course sweeping” in the first few units, then perform “prime coating” in the same few units, then shift to “base course sweeping” to finish off the remaining units, and finally perform “prime coating” in the remaining units. Because there is 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 movement of the crews on the construction site.

8. Work progress rate

For crash able activities, the activity progress rate is dependent on the number of crews or resource assigned to the activity. Almost any activity can be performed with a wide range of assigned resources. These assigned resources determine the activity's duration along the units by manipulating the duration of activity during scheduling. It is

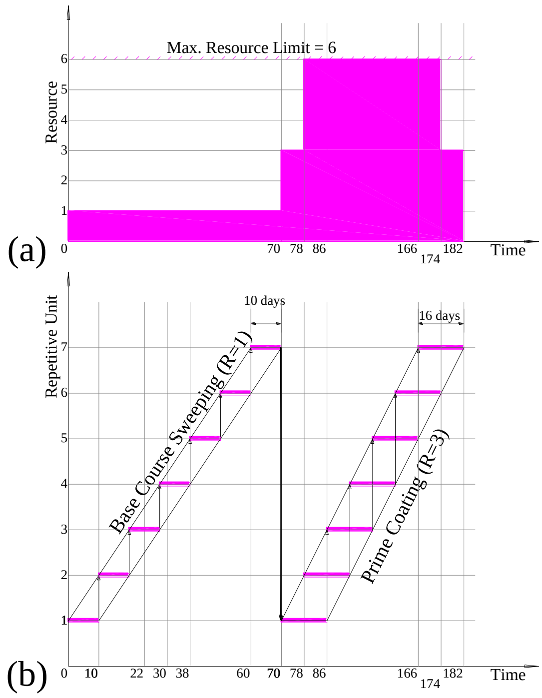

Fig. 4. Effect of resource limitations: (a) resource histogram; (b) project schedule.

possible to reduce or eliminate time delays resulting from logical constraints.

Man-hour estimates were obtained from field personnel who had many years of site experience, technical field specifications and/ or previous record. Mathematical models can be utilized to determine the optimum crew size. The activity duration thus obtained diverged sometimes from the performance actually achieved on site, and had to be corrected to better reflect actual conditions.

Arditi et al. [3] stated that the error introduced by such divergence, even if minimal, compounded to result in large deviations in the project duration, especially as repetition increased, fig. 5. For example, if the duration of "base coarse sweeping" is overestimated by r=25%, the correction of the error will reduce the duration by r% and increase the rate of production (PR) by the same percentage.

If the time ordinate ST(i) of the start of an activity is calculated, then it will be clear that r% error in the rate of production (PR) will be magnified by (N-1) times into significantly large deviations as repetition increases fig. 6.

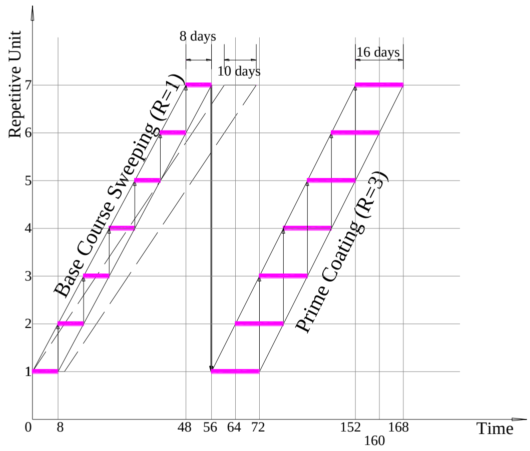

Fig. 5. Effect of overestimated activity duration.

This extreme sensitivity of the LOB method to errors in man-hour and subsequent duration estimates for each activity must be well recognized at the outset.

9. Workflow direction

Thabet, et al. [18] stated that the repetitive characteristic of work in multistory buildings forms chains of activities. Each activity chain posses a spatial orientation or workflow in the vertical direction. The direction of flow is either upward or downward.

9.1. Upward direction

Most work is scheduled in an upward direction to follow the construction of skeleton.

9.2. Downward direction

Some other construction activities, however, are scheduled in a downward direction for reasons (i.e., safety or to prevent damage of the installed work). The final finishing of external cladding, clearing, and cleaning may be typical examples of such types of activities, Fig. 6. The shown figure represents this type of workflow direction, which is not considered in the selected references.

10. Contractual milestones

Contractual milestones can be important constraints to be considered in scheduling a project using the LOB technique. Especially, 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 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 units. 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.

11. Learning phenomenon

The learning phenomenon whereby the actual duration of an activity is reduced as repetition increases is not part of the LOB method used in most literatures. The learning phenomenon does exist; it occurs however at every beginning of repetitive cycles. In case the rate of repetition is large, the effect of learning on the average activity duration may be assumed negligible. Strategically positioned time buffers could absorb whatever little effect there may be at the very beginning.

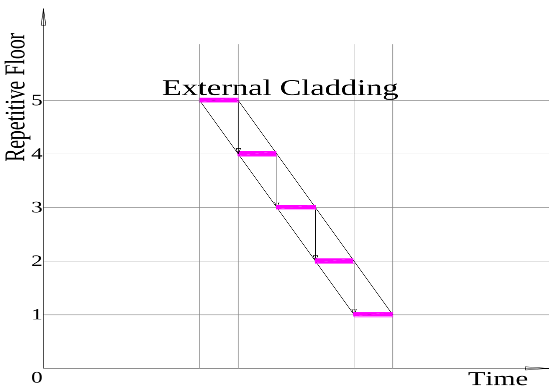

Fig. 6. Workflow in downward direction.

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. 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 [19].

12. Nonlinear and discrete construction process

Repetitive construction process may contain some nonlinear and non-repetitive (discrete) activities.

12.1. Nonlinear activities

In a high way project, earthwork will vary from section to section due to differences in the terrain, which is defined by nonlinearity in most literatures.

A nonlinear activity is characterized by repetitive operation where the output of operations is not uniform at every unit. 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.

12.2. Discrete activities

In a high way pavement project, the posting of the occasional sign structure is defined a discrete activity, which does not repeat itself in every unit.

The discrete portions of the project cannot be scheduled directly by the LOB method either, because these activities are not included in the typical 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.

13. Conclusions

Several issues associated with LOB applications have been identifies in this research. This research determines the practical limitations of LOB in scheduling repetitive construction units. The logical and strategic limitations associated with the characteristics of repetitive activities are presented. Learning phenomenon can play an important part in determining performance in certain activities. The following schedule constraints are discussed: (i) logical sequence, (ii) crew work continuity, (iii) number of employed crews, (iv) work crew size, (v) project resources, (vi) work progress rate, (vii) workflow direction, (viii) contractual milestones, (ix) learning phenomenon, in addition to (x) nonlinear and discrete construction process. These constraints with underlying principles are briefly discussed.

14. Recommendations

The previous constraints will be utilized in future work by the author to develop computer programs that are based on the classical LOB technology to maximize the benefits of learning curve, and to minimize idle waiting intervals of equipment and labors.

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