International Journal of Civil
Engineering (IJCE)
ISSN(P): 2278-9987; ISSN(E): 2278-9995
Vol. 3, Issue 5, Sep 2014, 37-46

International Academy of Science, Engineering and Technology
IASET Connecting Researchers; Nurturing Innovations

REPETITIVE PROJECT SCHEDULING: DEVELOPING CPM-LIKE ANALYTICAL CAPABILITIES

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ABSTRACT

Continuity of work over the successive units is the primary requirement for effective utilization of dedicated resources while scheduling repetitive construction projects. Critical path method (CPM) is the most commonly used method for scheduling construction projects. When CPM is used for scheduling repetitive construction projects, the continuity of work over successive units can not be ensured. To overcome this limitation of CPM in scheduling repetitive projects, a number of resource-driven scheduling approaches have been proposed over last thirty years. Most of these resource-driven scheduling methods are graphical and lack the analytical capabilities. In this paper, a new scheduling methodology to carry out CPM-like analysis is presented. This model ensures maximum possible crew work continuity and enables to determine the floats.

KEYWORDS: Repetitive Construction Projects, Scheduling, Critical Path, Crew Work Continuity

INTRODUCTION

Repetitive construction projects comprise of several similar units in which same tasks are repeated in a certain sequence. Projects like road construction, multi-storeyed building construction, mass housing construction, multiple spans bridges and pipeline laying involve repetitive construction over several similar units or locations. Usually, some dedicated resources are allocated for performing a particular task in all the repetitive units. These resources complete a task in one unit before moving to the next unit. Continuity of work over the successive units is the primary requirement for effective utilization of these dedicated resources.

The scheduling problem posed by repetitive projects is similar to the minimization of project duration subject to technical precedence constraints and resource continuity constraints. In repetitive projects, resource crews move from location to location and complete work that is prerequisite to starting work by the following resources. Hence for scheduling repetitive construction projects, all the tasks must be scheduled considering the precedence logic and the availability of the assigned crew for each activity at each unit. In repetitive construction projects, a resource crew is required to repeat the same task in a number of repetitive units in the project moving from one unit to another. As each dedicated resource crew move from one unit to another performing a specific task, a crew is required to wait if the crew of the preceding task has not finished its work in the particular unit (Yang and Ioannou 2001). For effective resource management, such unforced idleness must be avoided to provide continuity of work for each resource crew.

To maintain work continuity, repetitive units must be scheduled in such a way as to enable timely movement of crews from one unit to the next, avoiding crew idle time. Ensuring work continuity, during scheduling, provides for an efficient resource utilization strategy (El-Rayes and Moselhi 1998) that leads to (1) maximization of the benefits from the learning curve effect for each crew; (2) minimization of idle time of each crew, and (3) minimization of the off-on movement of crews on a project once work has begun.

The critical path method (CPM), the most commonly used construction scheduling method, is basically a duration-driven approach and hence not suitable for repetitive projects (Bhoyar and Parbat 2014). Though CPM has been used for many construction projects, it has been found inadequate for scheduling repetitive projects. The limitations of CPM to accurately model the scheduling requirements of the repetitive projects have been reported by Suhail and Neale (1994), Harris (1996), Harris and Ioannou (1998), Harmelink and Rowings (1998), Mattila and Park (2003) and Ipsilandis (2007). The first drawback is that networks become crowded due to presence of numerous repetitive units. The main shortcoming of CPM in repetitive project scheduling is its inability to ensure crew work continuity.

To overcome the drawbacks of network scheduling techniques, many other approaches have been developed, such as line of balance method, the vertical production method, time space scheduling method, time-space scheduling method, linear balance charts, velocity diagrams, the linear scheduling method and the repetitive scheduling model. In all these approaches, repetitive tasks are plotted as lines with constant or varying slopes, where the slopes represent the production rates. These alternative methods available for scheduling projects with repeating activities are termed as “linear scheduling” (LS) techniques. These graphical methods lack the analytical capabilities like CPM and hence are inadequate for determining activity floats and the critical path that governs the project duration.

In this paper, a new approach for scheduling of repetitive construction projects is presented. The proposed scheduling method combines the advantages of CPM as well as linear scheduling methods to meet the scheduling requirements of repetitive construction projects. This comprehensive analytical approach is capable of identifying critical path, much like CPM.

PROPOSED SCHEDULING METHOD

The proposed repetitive scheduling method involves four stages: 1) a forward pass that ensures precedence logic, crew availability and mandatory crew requirement for select tasks. This set the earliest possible project completion time, 2) a backward pass that ensures maximum crew work continuity. This establishes the scheduled start and finish times for each activity, 3) a late start schedule that establishes late start and finish times for each activity, and 4) float calculations. The forward pass and the backward pass calculations are adopted from Bhoyar and Parbat (2014a).

Consider a repetitive construction project comprising a set of tasks ‘i’ = $(1, 2, ..., I)$ to be executed over a number of successive repetitive units ‘j’ = $(1, 2, ..., J)$ with a set of finish-to-start precedence relationships. Let D_{ij} be the duration of an activity (i,j), denoting the time required to complete a task ‘i’ in a unit ‘j’. The predecessors and successors of task are denoted by sets ‘P’ and ‘S’.

Forward Pass

Start time of an activity according to precedence logic is given by,

$$SPL_{ij} = \left[EF_{(P_{(ik)})j} + Lag_{(P_{(ik)})i}\right]_{max} \tag{1}$$

For tasks without any predecessors, $SPL_{ij} = 0$.

Start time according to crew availability is given by,

$$SCA_{ij} = EPF_{i(j-1)} + Int_{ij} \tag{2}$$

In the first unit, $SCA_{ij} = 0$.

Hence, earliest possible start time for an activity,

$$EPS_{ij} = max\left[SPL_{ij}, SCA_{ij}\right] \tag{3}$$

Corresponding finish time is given by,

$$EPF_{ij} = EPS_{ij} + D_{ij} \tag{4}$$

If SPLij > SCAij, the crew of task ‘i’ is required to wait before starting work in unit ‘j’ after finishing work in unit ‘j-1’. Corresponding idle time is given by,

$$Idle_{ij} = SPL_{ij} - SCA_{i(j-1)} \tag{5}$$

For the work in first unit, $Idle_{ij} = 0$.

If it is mandatory to provide work continuity for task ‘i’,

$$Shift_{ij} = \sum_{k=j+1}^{J} Idle_{ik} \tag{6}$$

If crew work continuity is not mandatory for task ‘*i*’, $Shift_{ij} = 0$.

Hence, early start time for an activity is given by,

$$ES_{ij} = EPS_{ij} + Shift_{ij} \tag{7}$$

Corresponding early finish time,

$$EF_{ij} = ES_{ij} + D_{ij} \tag{8}$$

The minimum possible project duration is given by,

$$PD = max[\,EF_{iJ}] \text{ ------ } for,\ i = 1\ to\ I \tag{9}$$

The work-breaks for crew of the tasks without mandatory work continuity,

$$WB(ES)_{ij} = ES_{ij} - EF_{i(j-1)} - Int_{ij} \tag{10}$$

Backward Pass

Once earliest time to complete the project is established by forward pass calculations, starting with the last task, the activities are shifted from their earliest times to reduce the work-breaks, to the extent possible without affecting the earliest project duration. The scheduled start time and the finish time for minimum work-breaks are determined in this stage.

The shift time to pull activities forward to reduce work-breaks is given by,

For the tasks with no successors, (i.e. *NS (i)* = 0)

$$Shift_{ij} = \sum_{k=j+1}^{J} WB(ES)_{ik} \tag{11}$$

For other tasks, (i.e. *NS (i)* ≥ 1)

$$Shift_{ij} = min \begin{bmatrix} PS_{i,(j+1)} - EF_{i,j} - Int_{i(j+1)} ; \\ Start_{(s_{(ik)})j} - EF_{ij} - Lag_{(s_{(ik)})i} \end{bmatrix} \tag{12}$$

For the last unit activities, (i.e. $j = J$), $Shift_{ij} = 0$

Possible start time,

$$PS_{ij} = ES_{ij} + Shift_{ij} \tag{13}$$

Possible finish time,

$$PF_{ij} = PS_{ij} + D_{ij} \tag{14}$$

These activity times establish the maximum possible continuity of work for the crew of task (*i*) under the constraint of earliest possible project completion.

If a task is one of the multiple predecessors of its successor(s) and '$PS_{i,(j+1)} - EF_{i,j} - INT_{i(j+1)}$' is less than '$Start_{(s_{(ik)})j} - EF_{ij} - Lag_{(s_{(ik)})i}$', the task will have complete crew work continuity. Such task can be further pulled ahead in time without altering the schedule for succeeding task(s). The amount of this pull is limited to the least value of the pull time between the task and all its successors at all units.

$$LT_i = min\left[Start_{(s_{(ik)})j} - PF_{ij} - Lag_{i(s_{(ik)})}\right] \text{ ----- } \textit{for k =1 to NS(i) and j = 1 to J} \tag{15}$$

Shifting the entire task further by this least time retains the accomplished continuity of work for the crew of task (*i*) and creates additional room for shifting (pulling) its predecessor(s) for achieving corresponding continuity of work.

Hence, start time with minimum work-breaks,

$$Start_{ij} = PS_{ij} + LT_i \tag{16}$$

Corresponding finish time,

$$Finish_{ij} = Start_{ij} + D_{ij} \tag{17}$$

The computations are repeated for the preceding tasks to achieve the maximum possible continuity of work for their crew. The computational procedure is continued till the first task is scheduled for maximum possible continuity of work.

Late Start Schedule

Once the desired linear schedule for a RCP is obtained, the latest allowable start and finish times for each activity without affecting the earliest project completion time computed are required to be determined. For this, the activities are so scheduled to comply with the precedence logic and the crew availability. Starting with the last task (the task without any successor) in last unit and proceeding backwards through successive units (*J to 1*), activities are schedules to start and finish as late as possible.

For the tasks with no successors,

$$LF_{ij} = LS_{i(j+1)} - Int_{i(j+1)} \tag{18}$$

In last unit, (i.e. $j = J$), $LF_{iJ} = PD$.

For other tasks, (i.e. $NS(i) \geq 1$)

$$LF_{ij} = min\begin{bmatrix} LS_{i(j+1)} - Int_{i(j+1)}\ ; \\ LS_{(s_{(ik)})j} - Lag_{i(s_{(ik)})} \end{bmatrix} \tag{19}$$

Corresponding late start time,

$$LS_{ij} = LF_{ij} - D_{ij} \tag{20}$$

The computations are repeated for the preceding tasks till late finish and start times of the first task are determined. The late start and finish time calculations ensure the crew availability for that task in the succeeding unit as well as maintaining the precedence logic between the successive tasks. The late start schedule completely ignores crew work continuity.

Float Calculations

Comparison of the desired schedule and late start schedule reveals the time flexibility for scheduling tasks at different units. In CPM, float represents the excess time available for an activity. Total float is the excess time available without delaying the project beyond the scheduled finish time. Free float is the excess time available without delaying the scheduled start of the succeeding activity. Floats render flexibility in scheduling activities of a project. Criticality of an activity for timely project completion is judged from the float values. These concepts of floats and time criticality present in CPM can be adapted for linear schedules to provide some vital information for crucial decisions during project planning and execution.

Total Float,

$$TF_{ij} = LS_{ij} - Start_{ij} \tag{21}$$

Free Float,

$$FF_{ij} = min\begin{bmatrix} Start_{i(j+1)} - Finish_{ij} - Int_{i(j+1)}\ ; \\ Start_{(s_{(ik)})j} - Finish_{ij} - Lag_{i(s_{(ik)})} \end{bmatrix} \tag{22}$$

An activity is critical if its total float is zero. An activity (ij) is time critical if '$Start_{ij} = Finish_{(P_{(ik)})j}$'. An activity ($ij$) is resource critical if '$Start_{ij} > Finish_{(P_{(ik)})j}$'. If an activity is either resource critical or non-critical, there is flexibility in scheduling and executing that activity. A resource critical activity can be started earlier than its scheduled start without affecting project duration. A non-critical activity can be finished later than its scheduled finish without affecting project duration. For a linear schedule these flexibilities can be suitably expressed in terms of rate floats.

Unit production rate of an activity,

$$UPR_{ij} = \frac{1}{D_{ij}} \tag{23}$$

Rate float (total),

$$RF(T)_{ij} = \frac{1}{D_{ij}+TF_{ij}} \tag{24}$$

Rate float is the minimum allowable unit production rate for a task in a specific unit without affecting project duration.

ILLUSTRATIVE EXAMPLE

To demonstrate the utility of the proposed scheduling model a specific example project has been analysed. The project involves six discrete tasks to be repeated in six repetitive units. Task dependencies are shown in Figure 1.

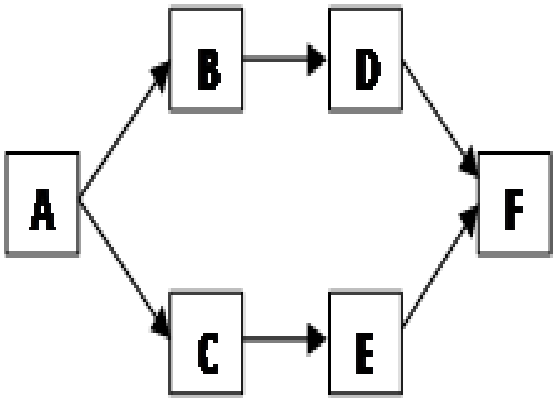

Figure 1: Network Representation of Six Tasks Project

The durations of each task at respective units, for a resource crew formation, are given in Table 1.

Table 1: Unit-Wise Durations for Six Tasks Project

Task No.	Task	Duration (Days)					
		Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6
1	A	6	6	8	8	6	6
2	B	2	2	2	2	2	2
3	C	4	4	4	4	4	4
4	D	7	7	7	7	7	7
5	E	8	8	8	8	8	8
6	F	6	6	6	6	6	6

IMPLEMENTATION

The proposed repetitive project scheduling model is implemented through a MATLAB program. The project data input is facilitated through Microsoft Office Excel spreadsheets. Similarly the resultant scheduling information is transferred to the spreadsheets in the same file where project data is input.

The resultant linear schedule with minimum work-breaks is shown in Figure 2. The linear plot for late start schedule is shown in Figure 3.

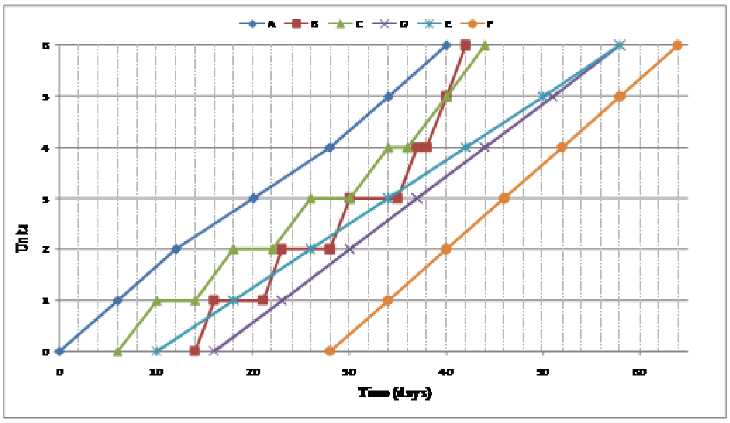

Figure 2: Linear Schedule with Minimum Work-Breaks for Six Tasks Project

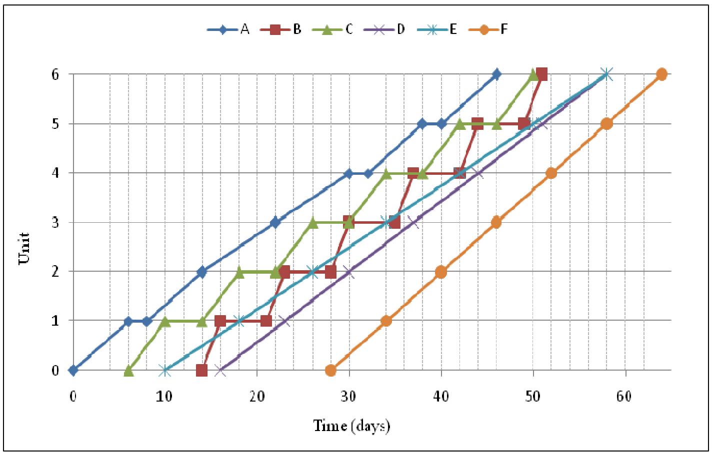

Figure 3: Late Start Schedule for Six Tasks Project

Table 2: gives the critical path metrics information.

Table 2: Critical Path Metrics for Six Tasks Project

Task	Unit	Total Float (Days)	Free Float (Days)	Criticality	Unit Production Rate (Unit/Time)	Rate Float (Unit/Time)
A	1	0	0	CR	1/6	1/6
	2	2	0	NC	1/6	1/8
	3	2	0	NC	1/8	1/10
	4	2	0	NC	1/8	1/10
	5	4	0	NC	1/6	1/10
	6	6	0	NC	1/6	1/12
B	1	0	0	RC	1/2	1/2
	2	0	0	RC	1/2	1/2
	3	0	0	RC	1/2	1/2
	4	0	0	RC	1/2	1/2
	5	4	0	NC	1/2	1/6
	6	9	9	NC	1/2	1/11
C	1	0	0	CR	1/4	1/4
	2	0	0	RC	1/4	1/4
	3	0	0	RC	1/4	1/4
	4	0	0	RC	1/4	1/4
	5	2	0	NC	1/4	1/6
	6	6	6	NC	1/4	1/8

Table 2: Contd.,

D	1	0	0	CR	1/7	1/7
	2	0	0	CR	1/7	1/7
	3	0	0	CR	1/7	1/7
	4	0	0	CR	1/7	1/7
	5	0	0	CR	1/7	1/7
	6	0	0	CR	1/7	1/7
E	1	0	0	CR	1/8	1/8
	2	0	0	CR	1/8	1/8
	3	0	0	CR	1/8	1/8
	4	0	0	CR	1/8	1/8
	5	0	0	CR	1/8	1/8
	6	0	0	CR	1/8	1/8
F	1	0	0	RC	1/6	1/6
	2	0	0	RC	1/6	1/6
	3	0	0	RC	1/6	1/6
	4	0	0	RC	1/6	1/6
	5	0	0	RC	1/6	1/6
	6	0	0	CR	1/6	1/6

CONCLUSIONS

One of the strong analytical features of CPM is the ability to identify the critical path. This path governs the project duration. For linear scheduling technique to be accepted as a valuable tool, it must be able to determine a set of critical activities, synonymous with those determined by CPM. In this paper, a method for determining the critical activities while scheduling repetitive projects is presented. Computations of rate floats reveal the time flexibility for non-critical activities.

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