Heuristic Repetitive Activity Scheduling Process for Networking Techniques

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Abstract

Project scheduling is a key activity in construction process. Networking Techniques are useful instruments to accomplish project planning and control. But Networking Techniques develop a discrete model of Construction Process which has instead a continuous nature. New Production theories like Critical Chain or Lean Construction recognize this as a major cause of construction process inefficiency. The difference between model and real building process can lead to managing problems for unexperienced planners, especially in repetitive projects like high rise buildings, housing, highways and other infrastructures, in which crews perform repetitive activities moving from one space unit to another. In particular networking techniques minimize construction total duration but do not satisfy the requirement of work continuity through repetitive units of the project. To satisfy the work continuity constraint many methods have been proposed by researchers and practitioners. Although the effectiveness of these methods, which give notable insights in repetitive construction process, construction scheduling is still performed in most real cases with a commercial software, working with a CPM based network like Precedence Diagramming Method (PDM). The objective of this paper is to present a simple, flexible and easy to implement optimization algorithm for resource-driven scheduling for repetitive projects. The algorithm is based on a PDM network plotted on a resource/space chart, thus identifying resource paths and unit paths in the network. After traditional PDM time analysis is performed, the algorithm seeks, for every repetitive activity to be performed on a repetitive space unit of the project, the Planned Start and the Planned Finish that are best suitable to satisfy the work continuity requirement. In order to maintain minimum project total duration the work continuity requirement is relaxed when encountering a network limit. According with Critical Chain Theory, time buffers are inserted at the end of every resource path, to prevent delays on project completion, due to resource unavailability. The method has been tested on a simple repetitive project from pertinent literature. The proposed algorithm is an heuristic resource-driven scheduling method for repetitive projects, easy to be implemented by practitioners.

Keywords: repetitive project, resource-constrained scheduling, precedence diagramming method, critical chain, lean construction
1. Introduction

1.1 Precedence Diagramming Method and Repetitive Projects

Construction Project scheduling is often accomplished with Activity Network. The most powerful networking technique now available for project planners is Precedence Diagramming Method (PDM) (Harris, 1978) which can be easily implemented with a computer software. PDM is a Critical Path Method (CPM) networking technique, so it is a construction model in which a set of elements, called activities, are linked each other with logical relationships. This construction model represents building process by means of time flow between the network or the sequence of the activities that constitutes construction phases. But at the same time it represents another flow in the network, the workflow. Actually network planning techniques are discrete and time oriented, instead construction process is a continue flow of operations. The success of network planning in term of use by construction planners is due to the fact that it is easily implemented by planning computer software, and that its model is well suitable to the traditional conceptualization of construction (Koskela, 1992). Construction activities may be repetitive or non repetitive. Repetitive activities are found commonly in the construction of high-rise buildings, pipeline networks, highway and housing projects. A repetitive activity is an activity which is part of a construction sub-process performed by specialized resources, like for instance plastering or masonry performed by crews in a multi-storey building. In fact, since construction is a continue process accomplished by resources, and the scheduling model (i.e. PDM) is discrete, experienced planners usually design an activity network in which construction activities are made discrete by the work assignment of a single constructive element, i.e. plaster for storey #1. So the continuous plastering sub-processes is modeled by means of a repetitive activity, plastering for every storey, i.e. space unit of the building. In a repetitive activity a construction crew often repeats the same work of that activity moving from one repetitive unit to another (El-Rayes and Moselhi, 1998). A non-repetitive activity is unique in the project and often coincide with the whole sub process, i.e. a central boiler installation of a facility (Halpin and Riggs, 1992). This kind of project activities, i.e. non repetitive, are easily implemented in network planning, often because of specialized resource utilization. In repetitive-unit projects instead, it is important that repetitive activities are planned in such a way as to enable timely movement of crews from one repetitive unit to the next, avoiding crew idle time. This is known as the “work continuity constraint” and El-Rayes and Moselhi (1998) observe that its application during project planning can provide an effective resource utilization strategy that leads to: maximization of the benefits from the learning curve effect for each crew; minimization of idle time of each crew; minimization of the off-on movement of crews on a project once work as begun.

1.2 Repetitive-Unit Project Scheduling

As a matter of fact the struggle of networking techniques to achieve the minimum project total duration may cause, especially in repetitive projects in which crews are employed from one repetitive unit to another, resource idle time in construction process. So networking techniques are considered in literature not suitable for the planning and scheduling of a repetitive project, especially because of
the inability to satisfy work continuity constraint, even if resource leveling is performed (Selinger, 1980; Reda, 1990; Russell and Wong, 1993). The basic instrument suggested by researchers and practitioners for the planning and scheduling of a repetitive projects are time / space diagrams, in which activities performed by resources are plotted as line or other geometrical shape. Researchers have proposed many scheduling methods, that can be classified as Line of Balance for Projects with discrete space units, like floors of high – rise building, factory buildings of an industrial plant, housing projects, and Linear Scheduling Method for continuous space projects, like highways and pipeline networks. The first class of repetitive projects is named as “discrete repetitive projects” while the second is named “continuous repetitive projects” (Yang and Ioannou 2001). Kenley and Seppänen (2010) observed that all these methods are more concerned with movement of resources trough locations or places, thus they introduced the Location-Based Management System (LBMS) which shifts the focus from individual discrete activities to managing the progress of repetitive activities as performed by crews moving through a building and completing all their work location by location. Selinger (1980) suggested that there is a tradeoff in scheduling repetitive projects: allowing work interruptions, thus violating crew work continuity constraint, may reduce the total duration of construction project, and accordingly, indirect cost, while may increase direct cost because of the idle crew and the learning effects on productivity. Russel and Caselton (1988) extended the work of Selinger in term of optimizing project duration while relaxing the work continuity constraint. Later, Russell and Wong (1993) suggested that the work continuity constraint should be satisfied but not strictly enforced in scheduling repetitive activities. In fact they experienced that many of the restrictive assumptions made in model implementing are not really important for practical implementation. Real life projects don’t follow the nice, neat parallel lines of a pure flow model, or the precision portrayed by network diagram. El-Rayes and Mosehli (1998) suggested that resource – driven scheduling accounts directly for crew work continuity and facilitate effective resource utilization. They suggested that resource – driven scheduling of repetitive activities requires the satisfaction of three constraint: precedence relationship, crew availability and crew work continuity. Basic concept of resource – driven scheduling of a repetitive project is to account for: a) numbers of crews to work simultaneously on different space units of repetitive activities; b) interruption of crew work continuity. As a matter of fact construction scheduling is still performed, in most cases, with a commercial software, like Primavera Project Planner® or MS Project®, working with a CPM based network. The objective of this paper is to present a simple, flexible and easy to implement optimization algorithm for resource-driven scheduling with repetitive and non-repetitive activities. The algorithm is based on a PDM network plotted on a resource/space chart. After traditional CPM time analysis is performed, the algorithm seeks the planned start and planned finish that are best suitable to satisfy the work continuity requirement, for every repetitive activity to be performed on a repetitive space unit of the project. The work continuity requirement is relaxed in order to maintain the minimum project total duration achieved by CPM time analysys. If it is possible the algorithm creates time buffers at the end of every resource path. Time buffers are needed to prevent delay on project completion (Goldratt and Cox, 2004).
2. New conceptualization of construction

2.1 Activity view and flow view of construction process

Starting from ages fifty of last century, scientist and researchers have been studying construction process to improve its efficiency and effectiveness. An important branch of research is about methods and instruments for project planning, scheduling and control. Basically the background of all this methods and instruments is the traditional conceptualization of construction. Construction is seen as a set of activities characterized by an input and an output, with the objective of producing a certain product. This is the “Activity View of Construction” (Koskela, 1992). This model of construction process originates from methods for contract accounting as defined in bidding contracts for construction. In fact building facility is divided in subsystems, set of technical compounds. The quantity surveyor sets relationships between technical elements and cost of manpower, materials and equipment. Actually, for every technical element of the building system it is estimated the cost of the conversion activity, which transforms input in output. The bidding contract sets for the building, or the building sub-system for sub-contract, the production output, and the prize to be paid, sum of single elements prizes, corresponding to conversion activities. The traditional conceptualization of construction is a model of construction which corresponds to a set of conversion activities, which are a set of production sub-processes that convert input in output, each of them realized by specialized crews and that can be analyzed and managed separately. Lean Construction is a construction management technique which has the goal of giving more value to the final client by building processes control. Management focus is on quality of product and processes improvement, waste (muda) reduction, operators responsibility and processes continuous improvement (kaizen). Construction processes are conceptualized as sum of conversion activities and flows of materials, energies, resources and information (Koskela, 1992). Building process conceptualization is now complete: it is the sum of Activity View and Flow View. That is the sum of two basic elements, conversion sub-processes, sets of conversion activities that add more value to the final product, and flow sub-processes, sets of flow activities that move product from one conversion activity to another, normally without value improvement for the final client. More building process efficiency can be achieved by flow activities elimination or reduction, or efficiency improvement of conversion activities. As a matter of fact networking planning techniques do not model construction flows, especially materials flows and crew flows. So poor planning management can lead to poor flows management, i.e. waste improvement. An experienced planner usually is well aware of flow processes, and keeps these flows as a back requirement of the construction plan (Yi, Lee and Choi, 2002).

2.2 Goldratt’s Critical Chain

Goldratt’s Theory of Constraints (TOC) and its direct application to Project Management, known as Critical Chain Scheduling (Goldratt and Cox 2004, Rand 2000) has recently emerged as a new approach to operation management. After the first period in the last decade of XX century, where TOC implementation in project scheduling met with some resistance, TOC approach was found by
researchers and practitioners to be the new approach to project scheduling that correlates planning tools and human behaviour (Steyn 2000). In fact TOC is a management philosophy that consider human behaviour in project planning and execution. Despite that project human resource management is normally seen as a field of study quite separate from tools and techniques of project time management, like Precedence Diagramming Method for example, Critical Chain project scheduling attempts to account for certain typical human behaviour patterns that affect project performance. Critical Chain focuses on the constraints of a project which prevent achieving its goals. Main concept of critical chain scheduling (Herroelen and Leus, 2001) is that critical chain is protected from time overruns with buffers. So the safety associated with the critical chain activities is shifted to the end of the critical chain in the form of a project buffer, which has the aim of protecting the project due date promised to the customer from variation in the critical chain activities. Feeding buffers are placed whenever a non-critical chain activity merge into the critical chain both to protect the critical chain from disruptions on the activities feeding it and to allow critical chain activities to start early in case things go well. Resource buffers are placed whenever a resource has a job on the critical chain and the previous critical chain activity is done by a different resource. Resource buffers are usually in the form of an advance warning. The execution of the project is managed through the use of buffer management. Since there is some predetermined part of buffer remaining unused, everything is assumed to go well, otherwise a corrective action must be taken. The execution of activities should be done according to roadrunner mentality: milestones are not used, thus allowing to capitalize on early finishes of task predecessor. Actually the core concept of critical chain scheduling is the optimization of work flow through the project.

3. Heuristic repetitive activity scheduling process for networking techniques

3.1 Proposed method

Construction planning with Precedence Diagramming (PDM) method includes three main phases: network realization, time analysis and plan optimization (Harris 1978). In the network realization phase network logic is defined, i.e. activities and logical relationships between predecessor activities and successor activities. In the time analysis phase forward pass is performed, and so early start (ES) and finish (EF) for every activity are computed and the minimum total project duration is found (TPD); then backward pass is performed and so late start (LS), late finish (LF) and floats for every activity are computed, and the critical path is found. In this phase feasible dates for activity performance are detected. In the schedule optimization phase construction programme is modified, searching to achieve project requirements satisfaction, and thus defining the target schedule. Project schedule optimization may change network logic, activity duration and time constraints. To improve construction planning and scheduling with Precedence Diagramming Method an heuristic repetitive activity scheduling process is defined, with the aim of supporting an inexperienced planner in defining target plan and schedule for a repetitive project. Project planning with Precedence Diagramming ensures logical precedence requirement satisfaction but does not ensure resource flow tracking, nor work continuity constraint satisfaction. These two critical elements of network planning
are tackled by the proposed method. Resource flow tracking is improved by network drawing. Network is plotted on a resource / space chart, with the x – axis representing resources and the y – axis representing space units of the project. Crews are grouped by work item, i.e. the repetitive activities of masonry, plastering etc. Multiple crews for every work item are allowed in order to perform the same repetitive activity in different space units at the same time. Activities are identified by a $ij-k$ code (figure 1) where $i$ identifies the work item, $j$ identifies single crew and $k$ identifies the space unit in which the activity is performed. An activity of a work item $i$, performed by the same crew $j$ in a set of space unit $k$ is called a repetitive activity.

The proposed method assumes that crews of the same work item have the same productivity rate in every space unit (Harris and Ioannou 1998). Plotting activity network on the resource / space chart enhances resources tracking and make possible to define resource-paths, $ij$ columns of the chart, and unit-paths, $k$ rows of the chart (Yi, Lee and Choi 2002, Moselhi and Hassanein 2004) (figure 2).

The work continuity requirement satisfaction is obtained by repetitive activity shifting. To ensure work continuity the proposed method introduce an algorithm that, after usual Precedence Diagramming time analysis, i.e. forward pass and backward pass, shifts the start and finish of repetitive activity to search for resource continuity, if made possible by network logic. In fact the optimization algorithm does not modify total project duration (TPD) as computed by traditional forward pass of Precedence Diagramming. The new start and finish dates are called Planned Start (PS) and Planned Finish (PF). If possible buffers (Time Buffer - TB) are placed at the end of every sub critical resource path $ij$ to protect the critical path from time overruns.
Idle time of crew, due to work interruption on a resource path $ij$, between $k'$ space unit and successor $k$ space unit is calculated as the subtraction of the early start of the successor repetitive activity in the unit $k$ and the early finish of the predecessor repetitive activity in the unit $k'$:

$$\text{Idle } ij \ (k',k) = \text{ES}_{ij-k} - \text{EF}_{ij-k}$$

(eq. 1)

where: $\text{Idle } ij \ (k',k)$ is the idle time of crew $ij$ between unit $k'$ and successor unit $k$; $\text{ES}_{ij-k}$ is the early start of the activity $ij-k$; $\text{EF}_{ij-k}$ is the early finish of the activity $ij-k$; $k'$ is the predecessor space unit; $k$ is the successor space unit.

- Rule 1: if, for every $k'$, $k$ couple of the resource path $ij$ the $\text{Idle } ij \ (k',k)$ value is equal to 0, or, for every activity $ij-k$ of the same resource path $ij$ the total float $\text{TF}_{ij-k}$ value is equal to 0, the resource path $ij$ is defined critical, although sub-critical.

Idle time of work on a space unit path $k$, between activities performed by $ij'$ resource and successor activity performed by $ij$ resource on the same unit path, is calculated as the subtraction of the early start of the successor repetitive activity of resource $ij$ and the early finish of the predecessor repetitive activity of the resource $ij$:

$$\text{Idle } k \ (ij',ij) = \text{ES}_{ij-k} - \text{EF}_{ij'-k}$$

(eq. 2)

where: $\text{Idle } k \ (ij',ij)$ is the idle time of work on space unit $k$ between activities performed by resource $ij'$ and resource $ij$; $\text{ES}_{ij-k}$ is the early start of the activity $ij-k$; $\text{EF}_{ij'-k}$ is the early finish of the activity $ij'-k$; $ij'$ is the predecessor resource path; $ij$ is the successor resource path.

- Rule 2: if, for every $ij'-k$, $ij-k$ couple of the space path $k$ the $\text{Idle } k \ (ij',ij)$ value is equal to 0, or, for every activity $ij-k$ of the same space path $k$ the total float $\text{TF}_{ij-k}$ is equal to 0, the space path $k$ is defined critical, although sub-critical.

Note that a critical space path or a critical resource path are not critical path in the original CPM sense, because they are usually defined by the idle time (eq. 1 and 2) which does not mean the absence of total float of the activities (with the exception of the rule 1 and 2, where actually the $\text{TF}_{ij-k}$ is equal to 0) but only the continuity of performance of a chain of activities on a space path or on a resource path. The chain of critical space or critical resource activities can still have float time in the CPM sense. To highlight this difference the original CPM critical path can be called “Time Critical Path”. If possible time buffers are placed at the end of every resource path to protect from contingencies the performance of activities placed on the Time Critical Path, thus preventing delays on project completion.

### 3.2 Scheduling Optimization Method

The proposed scheduling optimization method has two main phases, in which several steps are followed. The proposed algorithm of phase 2 is an heuristic method that search for project
optimization. The project solution can be sub-optima, but it is a simple method, easy to perform by researchers and practitioners.

**PHASE 1 – Path analysis**

1. Network logic. The PDM network is plotted on a resource – space chart, with the resources in the x – axis and space on the y – axis. Activities on the same k row show the work flow in the space unit (i.e. space path), activities on the same ij column show the work flow performed by the same crew j of a work item i (i.e. resource path).

2. Traditional PDM time analysis. Forward pass and early dates detection (ES and EF), backward pass and late dates detection (LS and LF). Free float and Total float calculation, time critical path detection (TFij-k = 0).

3. Resource critical path detection (eq. 1 and rule 1).

**PHASE 2 – Schedule optimization**

1. Analyze in the latest resource path ij the last activity ij-k:
   - if ij-k is time sub-critical with FFij-k > 0 = m ≠ 0 insert a Time Buffer (TBij) between ij-k and its successor, with TBij = t = m; the value of Planned Start is set to Early Start (PSij-k = ESij-k) and the value of Planned Finish is set to Early Finish (PFij-k = EFij-k). Then analyze the predecessor ij-k’ with Idle ij (k’, k) > 0 and go to step 2;
   - if ij-k is time critical with TFij-k = 0, or does not have any free float, (i.e. FFij-k = 0), the value of Planned Start is set to Early Start (PSij-k = ESij-k) and the value of Planned Finish is set to Early Finish (PFij-k = EFij-k). Then consider the predecessor ij-k’ with Idle ij (k’, k) > 0 and go to step 2. If every predecessor has Idle ij (k’, k) value equal to 0, go to the earlier resource path ij and re-start from step 1.

2. On the resource path ij, for the predecessor activity ij-k’:
   - the Free Float FFij-k’ = m is calculated;
   - the Idle Time of crew, due to work interruption between k’ space unit and successor k space unit (eq. 1) is calculated:
     \[ \text{Idle ij (k', k)} = \text{ESij-k'} - \text{EFij-k'} = n \]
   - activity ij-k’ is shifted of Sij-k’; where Sij-k’ = min (m, n) = s; the Planned Start and the Planned Finish are calculated as follows:
     \[ \text{PSij-k'} = \text{ESij-k'} + \text{Sij-k'} \]
the shift $S_{ij-k'}$ increases $Idle_{ij}$ ($k'$, $k''$) between activity $ij$-$k'$ and its predecessor $ij$-$k''$ on the same resource path $ij$, then go to step 3;

- if the activity $ij$-$k'$ has $TF_{ij-k'} = FF_{ij-k'} = 0$; or $Idle_{ij}$ ($k'$, $k$) = 0; the value of Planned Start is set to Early Start ($PS_{ij-k'} = ES_{ij-k'}$), and the value of Planned Finish is set to Early Finish ($PF_{ij-k'} = EF_{ij-k'}$); then go to step 3.

3. The $ij$-$k''$ predecessor activity of activity $ij$-$k'$ becomes itself $ij$-$k'$ of step 2; go to step 2. If there is no predecessor activity $ij$-$k''$ on the same resource path $ij$ go to step 1 and process the earlier resource path $ij$.

4. Sample Application

The proposed method is performed for a simple example. The example concerns a small construction project of refurbishment of a five storey building. Three repetitive activity are considered: concrete slab pouring (A), plastering (B) and paving (C). These repetitive activities must be performed by crews in every space unit of the project. Each space unit is a floor of the building. Every repetitive activity is performed by one or more than one crew. The example project has the following assumptions: only one crew for concrete slab pouring (A1) and for paving (C1), two crews for plastering (B1 and B2). Activity data for the example project are listed in table 1. In every space unit $k$ network logic is due to technological links between activities, so A – concrete slab pouring – is predecessor of B – plastering – and B is predecessor of C – paving – as shown in the activity network plotted on a resource / space chart in figure 3. Finish to Start relationships linking repetitive activities performed by the same crew in the different floors of the building trace resource flow in the project. The resource flow is set by project planner and in the example it is starting from unit 1 to unit 5. Proposed optimization method is then performed (figure 3 and 4).

<table>
<thead>
<tr>
<th>Repetitive Activity(i)</th>
<th>A - Concrete Slab Pouring</th>
<th>B - Plastering</th>
<th>C - Paving</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space Unit (k)</td>
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</table>
PHASE 1 – Path analysis. The PDM network is plotted on a resource – space chart (figure 3). Forward pass is performed and early dates are detected. Time critical path is formed by ij-k activities: A1-1, B1-1, C1-1, C1-2, C1-3, C1-4, C1-5. Idle time for resource path ij (eq. 1, rule 1) are non-zero only: for resource path B2 (Idle B2 (2,4) = 20 – 18 = 2); for resource path B1 (Idle B1 (1,3) = 15 – 13 = 2; Idle B1 (3,5) = 25 – 23 = 2). All resource path C1 is time critical, and so the resource continuity requirement is satisfied or anyway not optimizable. Resource path A1 is critical in the resource sense (rule 1), and so the resource continuity requirement is already satisfied.

PHASE 2 – Schedule optimization. At the end of resource path B2 it is inserted a time buffer equal to the free float value. The idle working time between unit 2 and successor unit 4 is equal to the free float of activity B2-2, which can be shifted of 2 days thus satisfying the resource continuity requirement for crew B2 (figure 4). At the end of resource path B1 it is inserted a time buffer equal to the free float value. The idle working time between unit 3 and successor unit 5 is equal to the free float of activity B1-3, which can also be shifted of 2 days, thus satisfying the resource continuity requirement for crew B1. The predecessor of B1-3 on the path B1 is activity B1-1, which has total float equal to 0 and idle working time between unit 1 and successor unit 3 equal to 4 (Idle B1 (1,3) = 17 – 13 = 4). This idle time can not be reduced because activity B1-1 is time critical. The optimization of resource path B1 between unit 1 and 3 would need to break at least one of the two schedule assumptions: maintaining minimum total project duration and/or change the resource production rate for activity B1-1. Anyway work continuity requirement was enhanced in the other two cases, for activity B1-3 and B1-5 and for resource path B2. As before mentioned, resource path A1 is already optimized, like path C1 (figure 4).
The proposed method has also been tested on a more complex repetitive project from pertinent literature, showing positive results even in this application.

5. Conclusion

With the aim of supporting an inexperienced planner in defining the target plan and schedule for a repetitive project, an heuristic repetitive activity scheduling process has been defined. The proposed method works with a CPM based network like Precedence Diagramming Method, and so can be easily implemented by researchers and practitioners. Two critical elements of network planning are tackled: resource flow tracking and work continuity constraint. The first with network drawing on a resource – space chart, the second with repetitive activity shifting, to search for work continuity. The method search for project optimization with an heuristic algorithm, so the found solution can be sub-optima, but of simple implementation.

Figure 4: Example network diagram - optimized schedule

References


