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Sustainable Project Schedule Management Using Pinch Analysis

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Project schedule management involves the proper allocation of resources, such as manpower. Human resource allocation practices generally lack a systematic method that will allow project managers to provide simple and sustainable planning solutions. A new scheduling methodology is proposed in this work, which integrates Pinch Analysis (PA) with critical path method (CPM) given a fixed project duration. The CPM with resource smoothing is the commonly used project management tool that defines the series of critical activities and other activities with slack. Resource smoothing is made when the fluctuation of needed resources does not have large variations with respect to the duration. This scenario gives a practical resource histogram and reduces the risk in project implementation. However, many resource smoothing algorithms use complex calculation and optimization processes that project managers do not easily understand. The hybrid CPM-PA is developed as a practical alternative and solution for this problem. In order to demonstrate the use of CPM-PA, a case study is considered, and the result is then compared with the traditional resource smoothing method. Results show that the new methodology produces results that are comparable to that of the traditional method. It achieved an acceptable Resource Improvement Coefficient (RIC). One of the advantages of the developed CPM-PA method is that it can produce graphical results that will allow project managers to identify bottleneck dates or Pinch Points easily. It is possible in practice to develop automated CPM-PA methods using spreadsheets for use in practical project management.

1. Introduction

Good project management is needed to arrive at a successful project. If not considered, the project will incur unwanted costs for the owner, contractor, and stakeholders, leading to unsustainable consumption of resources. Project management is the use of management skills, techniques, and knowledge to successfully meet the requirements of a given project (PMI, 2017). The critical path method (CPM) is a scheduling tool for determining minimum project duration and activities based on its logical network paths. Scheduling activities and optimizing resources go hand-in-hand, and one of the optimization techniques is resource smoothing. It is a technique wherein each activity's deadline is adjusted based on its float in order for a project to meet the completion date (PMI, 2017). A float, often referred to as 'slack,' is the amount of time a task can be delayed without affecting subsequent tasks or the overall project deadline. Projects are complex and composed of various tasks that are interlinked and dependent on each other; creating an optimal resource would be tedious and difficult. There have been numerous resource smoothing algorithms that have been created that produce optimal resources for a project. Resource smoothing is the procedure of scheduling activities to garner a low daily resource and possibly a leveled or 'smooth' histogram (Gordon and Tulip, 1997). A heuristic resource-leveling approach is to use the minimum moment method, and it assumes that, through optimizing activities on their floats, the optimal leveled resource histogram is where the moment is at its minimum (Christodoulou et al., 2015). However, a heuristic approach is tedious and time-consuming if given a massive project with complex and multiple activities. Alternative approaches based on metaheuristics such as genetic algorithms (GA) have also been reported in

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the literature (Leu et al., 2000). The pitfall of using resource smoothing algorithms is that they are computation-intensive.

Pinch Analysis (PA) is a methodology that was initially used for designing heat exchanger networks (HENs) by Linnhoff and Flower (1978) in order to combat the "energy crisis" (Kumana, 2002). The general principle of PA is the optimization of sources and sink stream matches while subjected to quality constraints; consequently, outsourcing of resources is minimized (Tan et al., 2015). From its earliest application, the growth and diversification of PA are documented in a handbook (Klemeš, 2013) and a review paper (Klemeš et al., 2018). A class of PA problems have been developed using time as the temperature analogue. This principle has been applied to supply chain planning (Singhvi and Shenoy, 2002), financial planning (Zhelev, 2005), short-term batch production scheduling (Foo et al., 2007), task scheduling (Foo et al., 2010), and renewable energy system design (Wan Alwi et al., 2012). More recently, it has been used for cash flow management in engineering projects, giving managers an overview of operations to be synchronized within the limits of a firm's cash flow (Ongpeng et al., 2019). Past research on PA application in scheduling uses time Pinch diagrams that determine the minimum outsourcing target for employees (Veeraragavan et al., 2018). Another study proposed combining graphical and mathematical optimization to simplify long-term and short-term maintenance planning (Chin et al., 2020). PA is particularly useful for small and medium-sized firms with limited access to sophisticated software tools (Lim et al., 2014).

To provide managers with scheduling management and circumvent such complex computational algorithms for resource smoothing, a hybrid CPM-PA approach is developed. The hybrid CPM-PA methodology comprises two primary features that integrate a scheduling algorithm (CPM) and resource smoothing (PA). The hybrid CPM-PA methodology is inspired by Foo et al.'s (2007) PA batch production scheduling. The proposed method can provide a visual representation of bottlenecks or Pinch Points wherein critical needs on resource management should be addressed. No previous publication on the integration of both CPM and PA in schedule management has been reported in the literature. The rest of the paper is organized as follows. Section 2 gives the formal problem statement. Section 3 describes the hybrid methodology. In Section 4, an illustrative case study is solved to demonstrate this approach. Section 5 gives the conclusions and prospects for future research.

2. Problem Statement

The known parameters in the proposed hybrid methodology are the following: (1) task, (2) duration of each task in d, (3) precedence network diagram, and (4) manpower requirement of each task. The method uses the CPM tool and integrates it with the PA approach in arriving at an acceptable resource smoothing histogram without any complicated calculations that include identifying bottlenecks or Pinch Points. The problem is to determine the daily minimum resources that conforms to proper smoothing or levelled distribution and at the same time identifying Pinch Point for project managers to easily identify risk.

3. Methodology

The hybrid CPM-PA approach has two parts: the scheduling using CPM seen in step 1 below and using PA in applying resource smoothing shown in steps 2 to 6 seen below. The CPM method is not explained in complete detail for brevity. It should be noted that the activity network diagram has been analyzed through CPM in order to determine the activities in the critical path. The proposed hybrid CPM-PA methodology is as follows:

Step 1. Creation of a Time-Scaled Network Diagram. It is a Gannt chart that illustrates the sequence of activities and their respective floats. In this step, the critical path determines which activities should not be delayed since doing so would increase project duration.

Step 2. Establish the Work Boundary System (WBS). The WBS is a boundary of work/activities where CPM-PA is applied locally to determine the minimum resource units (manpower) of that boundary. The boundaries of the WBS are the critical dates. The critical dates are the early start (ES) and finish dates (EF) of each activity in the critical path.

Step 3: Create the Limiting Deadline Table. It consists of the data points of a chosen WBS: ES, EF, and cumulative person-d. Further details are seen in the case study.

Step 4. Generating the Task Demand Curve. The data points from the limiting deadline table will be graphed wherein the x-axis will represent the person-d while the y-axis represents the duration.

Step 5. Generating the Task Composite Curve (TCC). Individual task demand curves will be combined into one curve called the TCC through superposition. Further details are seen in the case study.

Step 6: Targeting by use of a Process Line. In this step, the Pinch Point (PP) or the bottleneck of the TCC is determined, creating regions before PP and after PP.

Step 7: Summary: The daily minimum resource units of each WBS are calculated, and a resource histogram can now be done with a specific amount of manpower (in the y-axis) through time (in the x-axis). The Resource

Improvement Coefficient (RIC) of the CPM-PA and traditional resource smoothing is calculated using Eq(1) to compare results.

$$RIC = [n \cdot \Sigma(y_i^2)] / [\Sigma(y_i)^2] \quad (1)$$

wherein n = total days of the project, y_i = daily resource sum

4. Case Study

The CPM used in this illustrative example is taken from a reference (Halpin et al., 2017). Applying step 1, the logical network diagram of the entire project can be seen in Figure 1. The green highlighted arrows indicate the critical path of the network. For simplicity, only part of the network encircled in red is used here. The activity list of the case study can be seen in Table 1 wherein the activity/label and the duration, early start (ES), early finish (EF), float/slack in days, with required resources are summarized. The ES and EF are the schedules based from precedence diagram method as the earliest start and finish dates of each activity. In addition, the LS and LF are the schedules based from precedence diagram method as the latest start and finish dates of each activity. The activities that have a float/slack of zero (0) are on the critical path. The person-d in column 7 represent the product of the duration and resources of columns 2 and 6. The person-d represent the total work needed to accomplish a specific activity.

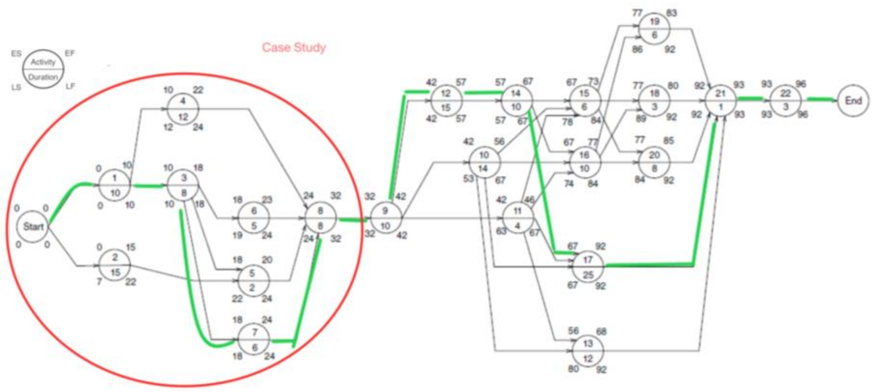

Figure 1: Entire Network Diagram of the Project (Halpin et al., 2017)

Table 1: Project description of the case study

1 **Activity**	2 **Duration (d)**	3 **ES (d)**	4 **EF (d)**	5 **Float (d)**	6 **Resources (Person)**	7 **Person-d**
1	10	0	10	0	4	40
2	15	0	15	3	9	135
3	8	10	18	0	7	56
4	12	10	22	2	7	84
5	2	18	20	2	10	20
6	5	18	23	1	2	10
7	6	18	24	0	4	24
8	8	24	32	0	9	72

Applying step 2, the time-scaled activity diagram and the work boundary system (WBS) are established. The critical dates are the ES and EF dates of each activity in the critical path, as seen in columns 3 and 4 in Table 1. The boundaries of WBS 1, 2, 3, and 4 are d 1-10, 11-18, 19-24, and 25-32 as illustrated in Figure 2. For this paper, WBS 1 is used as an example to explain the hybrid CPM-PA methodology to avoid redundancy. The same procedure applies to other WBS. Applying step 3, the limiting deadline table is made and shown in Table 2. Columns 1 to 4 are lifted from Table 1 with the addition of columns 5 and 6 as cumulative person-d for ES (CM_t (ES)) and EF (CM_t (EF)) per activity. The CM_t (ES) of Activity 1 is initialized at 0, while CM_t (EF) is the sum of columns 4 and 5 for the activity. For the next activity 2, the CM_t(EF) of the previous activity, activity 1, is equal to CM_t (ES). The CM_t (EF) of activity 2 is the sum of columns 4 and 5. Applying step 4, line segments are drawn up using Table 2 comprising of points (CM_t (ES), ES) and (CM_t (EF), EF) per activity. This is the task demand curve wherein the x-axis represent the person-d while the y-axis represents the days as seen in Figure 3. There are only two-line segments in this graph because there are only two activities in WBS 1.

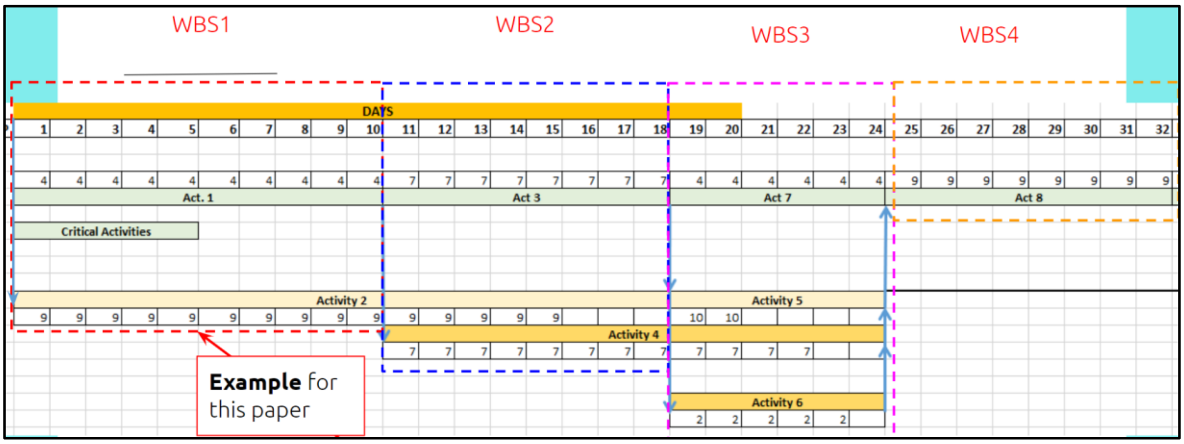

Figure 2: Time-Scaled Activity Diagram of the Case Study

Table 2: Limiting Deadline Table WBS1

1 Activity	2 ES (d)	3 EF (d)	4 Person-d	5 CM_t (ES)	6 CM_t (EF)
1	0	10	40	0	40
2	0	15	135	40	175

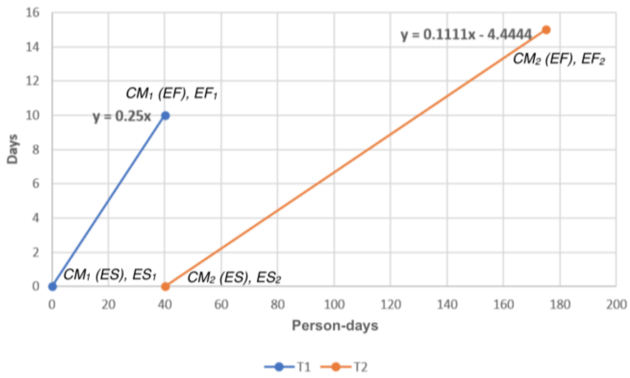

Figure 3: Task Demand Curve WBS1

Applying step 5, the individual segments are combined through the superposition called TCC, as shown in Figure 4. For days 0 to 10, the horizontal distances of activity 1 and 2 is 40 and 90 person-d giving a sum of 130 person-d. This sum is used as a point on the TCC with x- and y- coordinates as duration and the sum, arriving at (10 d, 130 person-d). For days 10 to 15, its starting point day 10 is from the previous calculated person-d which is 130 person-d. The y-coordinate value at day 15 is the horizontal distance of activity 2 is 45 person-d, from the difference of 175 and 130 person-d. On day 15, the sum is taken from 130 and 45 person-d, 175 person-d, and the new coordinate for TCC is at (15 d, 175 person-d). Applying step 6, the minimum resource units using targeting is commenced by creating a process line which is a line plotted from the positive (+) x-axis rotated counter-clockwise until it “Pinches” or touches the TCC, which is the Pinch Point (PP), see Figure 4. Targeting is the PA process of determining the minimum number of resource units. This is analogous to the process line in determining the resource units for batch production scheduling by Foo et al. (2007) and water processes by Wang and Smith (1995). After finding the PP, the TCC is divided into two sections: before PP and after PP. The minimum resource units before PP are determined by the reciprocal of the slope of the process line, while the resource units after PP are calculated by getting the reciprocal of each task demand curve of each activity.

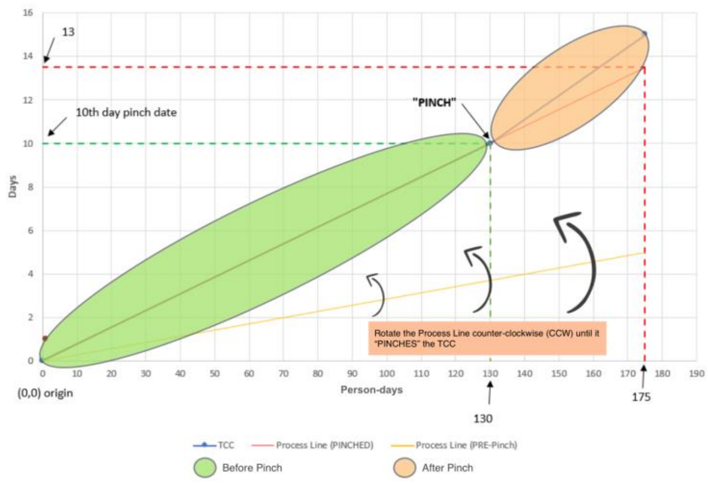

Figure 4: TCC of WBS1 with Process Line

Applying step 7, the minimum daily manpower for WBS1, 2, 3, and 4 are calculated and shown in Table 3. The value of the resource histogram is the sum of resources on the same duration, example from day 11 to 15, the resources from those inclusive dates are 9 and 14 person/d, having a sum of 23 person as seen in Figure 5. Variance from both methods in WBS 3, with 4 parallel activities, as seen from day 19 to 24 is observed where the CPM-PA maximizes the need for resources at the beginning and reduces the need at the latter part. The resource histogram produced by the hybrid CPM-PA approach is compared to the basic resource smoothing method in excel through the factorial method. The measurement of the performance is the resource improvement coefficient (RIC) metric. The resource histogram of the two methods can be seen in Figure 5. The RIC is a resource smoothing metric wherein the ideal value is 1. The RIC of the CPM-PA and sample traditional resource smoothing method is 1.138 and 1.102. This proves that hybrid CPM-PA produces a feasible resource histogram without the use of computer algorithms.

Table 3. Minimum Daily Manpower of each WBS

WBS	Pinch Point (d)	Minimum Resource (person/d) before PP	Minimum Resource (person/d) after PP
1	10	13	9 from d 11 – 15
2	15	14	14 from d 16 – 18
			7 from d 19 – 22
3	22	11	6 from d 23 – 24
			4 from d 24 – 25
4	No PP since there is only 1 activity		9

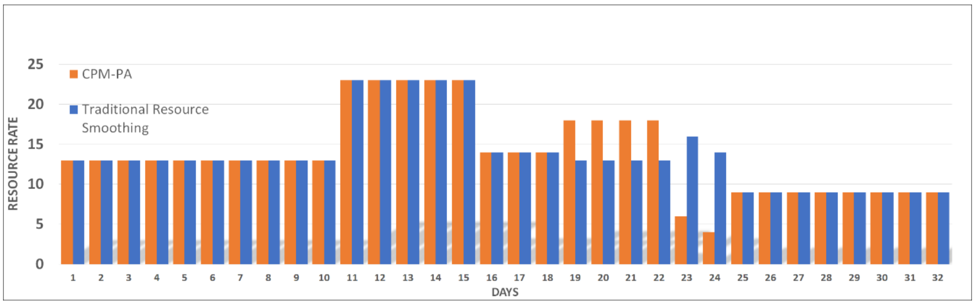

Figure 5: Resource Histogram PA-CPM vs Traditional

5. Conclusions

In this paper, an integrated CPM and PA method was developed for addressing resource smoothing problems in projects. The performance of the developed CPM-PA in the case study is the same using conventional method for WBS having less than 4 activities. For WBS that contains 4 or more activities, which is shown in WBS 3, the assignment of more resources at the beginning of the WBS is observed. Further investigation on CPM-PA is recommended to understand how the Pinch occurs for complex parallel activities. The results showed that CPM-PA produces an acceptable resource histogram for a project containing a complex precedence diagram network. The RIC values are acceptable as compared to traditional resource smoothing techniques. In addition, it allows an excellent visual representation of bottlenecks or PP for project managers on the possible risk on resource availability. Schedule management applying resource smoothing in making projects sustainable is a challenge due to complex calculations that project managers do not easily understand. It is recommended to develop time-scaled network and an automated CPM-PA method that can fit complex precedence diagram networks.

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