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A PROPOSED APPROACH FOR APPLYING CCPM CONCEPTS IN CONSTRUCTION

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Abstract— *For many construction projects, It is common for the customer to pay an incentive to the contractor for finishing the project in a shorter length of time. In contrast, the contractor pays delay penalties if the project is delayed. Goldratt 1997 suggested critical chain project management method (CCPM) as an attempt for minimizing project duration. Goldratt approach and related buffer sizing approaches result in different values of project buffer and feeding buffer which do not satisfy construction projects circumstances. The proposed model uses multiple shifts and discrete relationship between activity time and cost to be solved by integer programming to express real-life construction projects, optimize project duration with minimum cost and overcome CCPM such as Student's Syndrome, Parkinson's Law and Multi-tasking. A simplified representation of a small example project is formulated to represent this model. Application to a Cable Stayed Bridge is included. Final solution shows that this method is simple and can be applicable for construction of mega projects to generate a shorter time at low cost.*

Keywords: *CCPM, multiple shifts, integer programming, discrete relationship between time and cost, Prochain, Cable Stayed Bridge*

I. INTRODUCTION

Critical Chain Project Management (CCPM) was developed in 1997 by Goldratt. CCPM aims at delivering the projects faster as compared to traditional CPM method and achieves it through the process of waste reduction. The activity estimates in CPM are based on safe estimate whereas CCPM reduces the duration of activity to 50% of its original duration and uses the remaining 50% duration as buffer to protect the activity against delays (Waghmare and Bhan 2017). The major difference between critical chain method and critical path method is that the uncertainty of activity duration and limited resources are additionally considered in critical chain method (Wuliang et al, 2013).

The first step for CCPM consists of developing an initial schedule for the project activities with their duration estimates. This is done while taking into account the dependencies among the activities (as reflected in the project network) and the availability of resources. At this point CCPM identifies the "Critical Chain" as the set of activities that results in the longest path to project completion after resource leveling (Raz, 2001). The next step in CCPM planning consists of recalculating the project schedule based on shortened activity duration estimates. The rationale of CCPM for shortening the original duration estimates is as follows:-
A. Reduce individual activity estimates by 50 percent. The remaining 50% duration is used as Buffer.
B. Set Feeding buffer (FB) (half of the summation of non-critical chain activities buffers) at points where non-critical chain intersects the critical chain.
C. Set Project Buffer (PB) (half of the summation of critical chain activities buffers) at the end of critical chain.

Prochain Project Scheduling is software that can help to implement critical chain scheduling and buffer management. It is an addition to Microsoft Project. The schedule protects against cumulative activity uncertainty by adding project buffers which help ensure on-time delivery of the end dates (Prochain Solutions 2015).

CCPM is addressed to provide main concepts, including **(A)** minimizing project duration by removing hidden safety time using buffer types; **(B)** Student's Syndrome which is similar to when students are given assignments, they usually start assignments at the last minute even the length of time are enough. This leads to wasting any buffers built into individual activity duration estimates; **(C)** Parkinson's Law: People will simply adjust the level of effort to keep busy for the entire activity schedule. Usually, people do not promote be early even they can finish the work ahead of schedule (Leach 2000); and **(D)** Multi-tasking: the effect of multitasking should be considered because that fragmentation of resource and equipment's set up time would cause activities to delay due to loss of concentration (Hegazy2002).

II. RESEARCH MOTIVATION

Many attempts to improve Goldratt method initiated the development of new approaches concerning buffer sizing techniques. Literature review of CCPM and related buffer sizing approaches show that CCPM has advantages and disadvantages as detailed next.

Prajapati and Yadav 2017, summarized the advantages of CCPM as the following:-

1. It will be resulted into faster completion of projects than any other scheduling techniques.
2. It is based on resource dependencies to insure that non-critical activities will not become critical in future, that mainly happen in traditional method due to avoidance of resources required for project.
3. It will ensure elimination of multi-tasking within the given project. This can be made by identifying resource conflicts and resolve them by starting with the activity that is closest to the project completion date or with the activity that shows most resource conflict.
4. It considers human behavior during scheduling so improving workers attitude within project environment.
5. It will provide very simple way of tracking and monitoring project progress.

Disadvantages of CCPM are summarized as the following:-

1. Goldratt method cut 50% of activity duration as buffer but this percentage does not satisfy construction projects. Sharma and Yadav 2017, mentioned that if focusing on the specific construction industry projects then the method of calculation of project buffer is not appropriate.
2. Critical chain method requires the noncritical activities to be executed as late as possible to minimize any work in process and reduces behaviors called "student syndrome" and "Parkinson's law" (Kendall et al. 2001). However, Peng et al 2012 presented a revised critical chain method for the projects which is defined as active critical chain method (ACCM), where all activities are scheduled as early as possible to avoid the risk of project delay in software development projects.
3. CCPM reduces project duration without any consideration of project cost although project duration and cost are related.

Disadvantages of CCPM show that we cannot depend on this method to minimize construction projects duration. To overcome disadvantages of CCPM related to the construction projects, the authors propose that:-

1. Time cost trade-off and multiple shifts are used to minimize construction project duration with minimum cost especially in case of constrained completion date, limit availability of resources especially machines, and site congestion. Activity discrete relationship between time and cost is used to express real life construction projects circumstances.
2. Non-critical activities will be scheduled in their early start dates to avoid any delays in project completion date.
3. Using constrained related activities in shifts to overcome multitasking. Shifts system can be applied in case of two or three constrained related activities. Each shift can be used for execution one activity.
4. Realizing of project importance and its value and working 24 hours a day in multiple shifts system are motivation for labors not to waste time and concentrate on finishing activities in their time. So, multiple shifts can be used to overcome Student's Syndrome and Parkinson's Law.

III. TIME-COST TRADE-OFF PROBLEM

The objective of time–cost trade-off is to minimize project duration with minimum cost. This section discusses on determining applicable method for project compression, discrete activity time-cost relationship, and using multiple shifts in construction projects for minimizing project cost.

3.1. Activity Discrete Time-Cost Relationship

The discrete time–cost trade-off problem, which was introduced by Hindelang and Muth (1979), is an important subject in project scheduling theory and applications.

The discrete time-cost trade-off assumes that each activity in the project has several alternative construction methods, and that each method has its own duration and cost (Chen and Weng, 2009). This assumption is justified because an activity can have alternatives to be executed with different methods, crews, equipment, etc. Of course, each alternative has its corresponding cost and duration.

Eldosouky et al. (1991) used two examples of the most repetitive construction activities (excavation and/ or placing concrete) to identify the realistic relationship between the duration and cost for construction activities with different working conditions such as multiple shifts, increasing resources and working overtime. It has been proven that the discrete relationship is the correct representation of the relation between the duration and cost of a construction activity.

3.2. Project Compression using Mathematical Methods

The main concept is to formulate the problem in a systematic procedure that must take the standard form of mathematical programming.

Mayer and Shaffer 1965, introduced zero-one variables; to insure that only one of the discrete points (X)s exists in the solution. The duration and cost of activities are given by:

$$(\mathbf{C})i=(\mathbf{C1})i+\{\textstyle\sum_{j=2}^{m}(\mathbf{Cj}-\mathbf{C1})\ \mathbf{Xj}\}i \quad (1)$$

$$(\mathbf{d})i=(\mathbf{d1})i-\{\textstyle\sum_{j=2}^{m}(\mathbf{dj}-\mathbf{d1})\ \mathbf{Xj}\}i \quad (2)$$

Where, m is the number of discrete points for the activity (i). Subtracting (C1) and (d1) from each (C) and (d) in equations (1) and (2) respectively, means that zero-one variables corresponding to the discrete point number (1) is extracted in these equations. Thus reducing number of variables for each activity by (1), Xj is zero-one variables of activity (i).

However, Eldosouky et al. (1991), determined the cost of an activity (C)j in terms of zero-one variables as follows:

$$(\mathbf{Cost})_j=\textstyle\sum_{k=1}^{kj} c_{jK}X_{jK} \quad (3)$$

Where, C_{jK} is the kth direct cost of activity (j), Xj is zero-one variables of activity (j),and (Kj) is the number of discrete points for activity (j).

3.3. Utilization of Multiple Shifts in Construction Projects

The utilization of multiple shifts schedule is very effective and potential solution at reducing project duration. Multiple shifts involve hiring second and third crews of workers to work after the first crew.

The utilization of multiple shifts is reported to provide a number of advantages, including **(1)** doubling or tripling weekly work-hours; **(2)** lowering the required premium costs for evening and/or night shifts compared to those of overtime hours; **(3)** Lack of immediate fatigue factors compared with working overtime; and **(4)** No congestion factors resulting in overmanning (Hanna et al. 2008).

Despite these advantages, the utilization of multiple shifts still has a number of limitations including its negative impacts on construction, cost, productivity, and safety. Accordingly, the utilization of evening and night shifts is reported to cause: **(1)** Productivity losses due to workers fatigue, health disorder, and lower morale (Kogi 1985). **(2)** Increasing the risk of injuries and accident rate (Folkard and Tucker 2003). **(3)** Little cooperation between shifts, inconsistent operating procedures across shifts, inefficient communication between crews, and absence of regular business hours for management (Penkala 1997).

These are important factors which can impact on project performance and cost, but if there is a large and important projects that require work beyond a standard shift and there is the ability to perform work at night, shift work can be useful. This is especially true for extremely hot climates, where productivity at night when the temperatures are cooler is actually higher than during the day. (Hanna et al. 2008).

3.4. Impact of shift work on labor productivity

In general, the productivity losses due to shift work come from supervisory, coordination and transition problems. This makes it hard to quantify the actual amount that it will affect a project and it is dependent on the organization and type of work. The reason shift work has not been used is because its application is limited. It practically should be used on larger projects, where shift work would be used for an extended period of time (Ibbs 2015).

However, Waldron 1968, estimated the productivity loss due to shift work to be 10%. On the other hand, total project cost of shift work is normally higher than that of normal operation. Shift work introduces other additional costs, including additional administration personnel, supervision, quality control, safety, and lighting. Direct costs of shift work are approximately 20% extra in wages (Hanna etal, 2008).

3.5. Using multiple shifts in construction projects in Egypt

Interviews with more than twenty Egyptian engineers project managers, site managers, site engineers, and supervisor engineers in different construction projects such as infrastructure, residential, electric substation, oil and gas projects highlight that:-

1. Using multiple shifts of activities that are executed depending on machines as main resources is very useful because of low temperature, easy movement in the site, and traffic flow. Also, most engineers mention that production rates do not change in the second shift and third shift. So, machines can work on double or triple shifts without productivity losses with changing labor crews from shift to other. In such activities, daily rates of labors in the second shift and third shift increase by 25-50% which represents 5-10% of activity cost. Efficiency and maintenance of machine and their effect on productivity and cost can be considered in the projects.

2. Using multiple shifts of activities that are executed depending on labors as main resources is useful for large projects. Production rates of the second shift decrease by 15-20% and production rates of the third shift decrease by 25-35% regarding to the first shift. Daily rates of labors on second shift and third shift increase by 25% and 50% regarding to the first shift which represent 10-20% of activity cost. Some engineers mention that production rates decrease by a small amount between 5-10% if the system of multiple shifts is maintained for long period of time.

So, the proposed model is formulated depending on the production rate of the evening shifts decreased by 20% and night shifts by 30%, the activity cost of the evening shift increased by 10% of the normal cost, and the activity cost of night shift increased by 20% of the normal cost for activities that use labors as main resources in its execution. Production rates do not change of activities that use machines as main resources in its execution and the activity cost of the evening shift increased by 5% of the normal cost, while the activity cost of night shift increased by 10% of the normal cost.

3.6. Constrained Related Activities in Shifts:

In general, machines are key resource in construction projects. In some cases, there are two or three activities that are affected by using the same machine as a main resource. These activities are called constrained related activities and must be treated together in planning. Shifts system is used to treat this problem for minimizing project duration and to overcome such constrained related activities. Shifts system can be applied in case of two or three constrained related activities. Each shift can be used for execution of one activity by the same machine.

IV. The Proposed Model Formulation

The proposed approach includes the following four phases as detail in this section.

4.1. Perform Network Analysis Considering Normal Activities Durations and Costs

The first step in the proposed model is to perform network time analysis considering normal activities' durations and costs. Activity duration estimates are quantitative assessments of the likely number of time periods that are required to complete an activity. Project management software such as primavera P6 or Microsoft Project can be used for these phase. MS Project software will be used to formulate the proposed model.

4.2. Mathematical Statement by Integer Programming

The activities comprising a construction project could be classified into a number of groups according to the key resources which affect the planning of these activities. Each group (i) could contain a certain number of activities. The utility data for each activity (j) could be represented by a number of discrete points. Therefore, the following notations are introduced:
I :number of groups of activities in a project.
Ji : number of activities in group (i), and
Kj : number of discrete points for activity (j).

4.2.1. Decision Variables

In the formulation of the problem, two kinds of decision variables will be used. These are:
ZERO-ONE VARIABLES; (**X**), and
ACTIVITIES SCHEDULED START; (**SS**).

An integer variable (**X**) is introduced which represent choice of one or double or triple shifts of non-related activities and choice of first or second or third shift of constrained related activities, and will have the value of zero or one only. On the other hand, the activities scheduled start decision variables will be used to satisfy the proper sequence of activities in the project.

4.2.2. Objective Function

The objective of the problem is to complete the project within most economical duration by expediting certain activities keeping the overall costs at a minimum. Therefore, the objective function to be minimized is the cost of the project.
The cost of an activity (C)j , in terms of zero-one variables, could be defined as follows:

$$\textbf{(Cost)j} = \sum_{k=1}^{kj} cj_K \, X_{jK} \qquad (3)$$

Where, C_{jK} is the kth direct cost of activity (j)
The cost of a group (i) is the summation of costs of all the individual activities comprising the group. Therefore:

$$\textbf{(Group Cost)i = Ci = (C)1 + (C)2 …+. (C)Ji} \qquad (4)$$

Substituting from Eq. (3) into Eq. (4), the cost of group (i) will be:

$$Ci = \sum_{j=1}^{Ji} . \sum_{k=1}^{kj} c_{\,jK} \, X_{\,jK} \qquad (5)$$

So, the direct cost of the project (PDC) is the summation of costs of all groups of activities in the project. Therefore,

$$\mathbf{PDC=\sum_{i=1}^{I}\sum_{j=1}^{Ji}.\sum_{k=1}^{kj}.C_{ijK}\ \ X_{ijK}} \tag{6}$$

Indirect cost of the project is calculated by multiplying completion time of the project and indirect cost of unit time. The project indirect cost, therefore, is:

$$\textbf{Project indirect cost} = \mathbf{Y * SF} \tag{7}$$

Where, (Y) is the indirect cost of unit time of the project.
(SF) is the required scheduled finish or completion time of the project.
So, the total cost of the project (PC) is the summation of direct cost and indirect cost of the project. The project total cost (PC), therefore, is:

$$\mathbf{PC=\sum_{i=1}^{I}.\sum_{j=1}^{Ji}.\sum_{k=1}^{kj} c_{\ ijK}\ X_{ijK}\ \ + Y * SF} \tag{8}$$

4.2.3. Problem Constraints

A. Zero—one constraints: to insure that only one discrete point is considered for each activity. The condition for satisfying this criterion for the activity (j) is:

$$\mathbf{\sum_{k=1}^{kj} X_{jKj}=1\ ,}\quad X \geq 0;\ \text{integer} \tag{9}$$

Where, (Kj) is the number of discrete points for activity (j).

B. Constrained Related activities:
The zero-one decision variables could be used also to satisfy the selection of the corresponding discrete points for the constrained related activities. This means that choosing a certain point for an activity in a group of constrained related activities in one of three shifts requires the selection of the points for the other activities in the group to work in the second and third shifts. The constrained related activities that are based on working each activity in one of three shifts could be satisfied by the following constraints:

$$\mathbf{\sum_{j=1}^{i} Xj1=1,\quad \sum_{j=1}^{i} Xj2=1,\quad \sum_{j=1}^{i} Xj3=1} \tag{10}$$

Where, (j) is the number of constrained related activities.

C. Network logic constraints: that will satisfy the proper sequence of activities in the project. Network logic constraints include scheduled start constraints and project completion constraint. The logic of network can be satisfied by considering a precedence constraint for each activity with its immediate predecessor(s). In total, these precedence constraints determine the project duration, since the project duration is the finish time of last activity in the project.

The duration of an activity (j), in terms of zero-one variables, could be defined as follows:

$$\mathbf{(D)_j\ =\ \sum_{k=1}^{kj} d_{jK}\quad X_{\ jK}} \tag{11}$$

Where, (d_{jk}) is the k^{th} duration of activity (j).

The scheduled start of an activity (m), (SS), is equal to the greatest scheduled finish of its preceding activities as follow:

$$\mathbf{SS_m \geq SF_j} \tag{12}$$

The scheduled finish of an activity is the scheduled start of the activity plus its duration. Therefore, the scheduled finish for an activity (j) is:-

$$\mathbf{SF_j = SS_j + D_j} \tag{13}$$

If there are (NS_j) successors for activity (j), Eq.(14) must be considered (NS) times;

$$\mathbf{SS_j + D_j - SS_m \leq 0 \qquad m=1,2,\ldots.., NS_j} \tag{14}$$

Substituting for D, of Eq.(11) into Eq.(14) and rewrite. It gives:

$$SS_j+\sum_{k=1}^{kj} dj_K X_{jK} - SS_m \leq 0, \quad m=1,2,.., NS_j \quad (15)$$

The finish time of the last activity (n) is its start time plus its duration. The project completion constraint, therefore, is:

$$SS_n + D_n - SF <= 0 \quad (16)$$

Where: SF is the scheduled finish or completion time of the project.

4.3. Determine Most Economical Solution for Project Cost and Duration Using LINGO

LINGO is a comprehensive tool designed to make building and solving mathematical optimization models easier and more efficient by finding the answer that yields the best result. LINGO provides a completely integrated package that includes a powerful language for expressing optimization models (LINGO.com 2017). To get results without any fractions, it should add to the model generate integer variables which can add in LINGO program as the following appreciations:
GIN (X_1, X_2, …….etc.) for Zero-One constraints, and GIN (SS_A, SS_B,….etc.) for Scheduled start constraints.
Where GIN X_1 is the abbreviation of generate integer for variable X_1
Project duration is determined as the scheduled finish or completion time of the project (SF). It is the optimum duration which is associated with minimum project cost.

V. EXAMPLE OF PROBLEM FORMULATION

For the purpose of demonstration of problem formulation, consider the simple project consists of (13) activities studied by Leach 2014.

5.1 Project Utility Data

Data for an activity contains its durations and the corresponding costs. The first point belongs to the normal duration and cost, while the last point refers to the crash duration and cost. The durations and direct costs are given in table 1. The durations; (d), are given in days and the costs; (c), are given in Egyptian pound (LE). Indirect cost of the project is assumed to be LE 5000 per day. So, the indirect cost for project normal duration of 85 days is LE.425000. Normal cost of the project is the summation of activities normal costs = LE. 849600, and the Project normal total cost = 849600 + 425000 = LE. 1274600.

Table 1. Utility data for the example problem

Group	Activity Name	Direct Cost					
		one shift or 1st shift		Double shifts or 2nd shift		Triple shifts or 3rd shift	
		Duration	Cost	Duration	Cost	Duration	Cost
(1)	Act. A1	16	100000	16	105000	16	110000
	Act. A2	17	125000	17	131250	17	137500
	Act. A3	28	225000	28	236250	28	247500
(2)	Act B1	8	82000	8	86100	8	90200
	Act. B2	8	35000	8	36750	8	38500
	Act. B3	16	42000	16	44100	16	46200
(3)	Act. C1	4	60000	4	63000	4	66000
	Act. C2	4	29000	4	30450	4	31900
	Act. C3	6	36000	6	37800	6	39600
(4)	Act. D	10	9600	6	12096	4	12672
	Act. E	13	24000	8	31015	6	36554
	Act. F	6	72000	4	100800	3	118800
	Act. G	6	10000	4	14000	3	16500

Table 1 shows that the project is divided into (4) groups as follow:-
1- Groups (1), (2), and (3) have constrained related activities. %increase percentage in Cost of the second and third shifts is 5%, and 10% of first shift. For example activity (A1) has 16 days with cost of LE.100000 in case of execution this activity in the first shift. The cost of activity is (100000*1.05=LE.105000) in case of the second shift and (100000*1.1=LE.110000) in case of the third shift.

2- Group (4) has non related activities. %increase percentage in Cost of the second and third shifts is 10%, and 20% of first shift. For example activity (D) has 10 days with cost of 9600 in case of execution this activity in one shift. In case of execution this activity in double shifts the cost of activity is (0.6*9600+0.6*9600*1.1=LE.12096). In case of execution this activity in triple shifts the cost of activity is (0.4*9600+0.4*9600*1.1+0.4*9600*1.2=LE.12672).

The project was previously solved using Goldratt method using Prochain scheduling software as shown in figure1. Figure 1 illustrates that project activities durations decreased by 50%. The Critical Chain contains activities A3, A2, A1, B1, C1, D, E, F, and G with total duration 55 days. Project buffer calculated as half of critical chain duration is 28 days. So, project duration is equal the summation of critical chain duration and project buffer or 83 days.

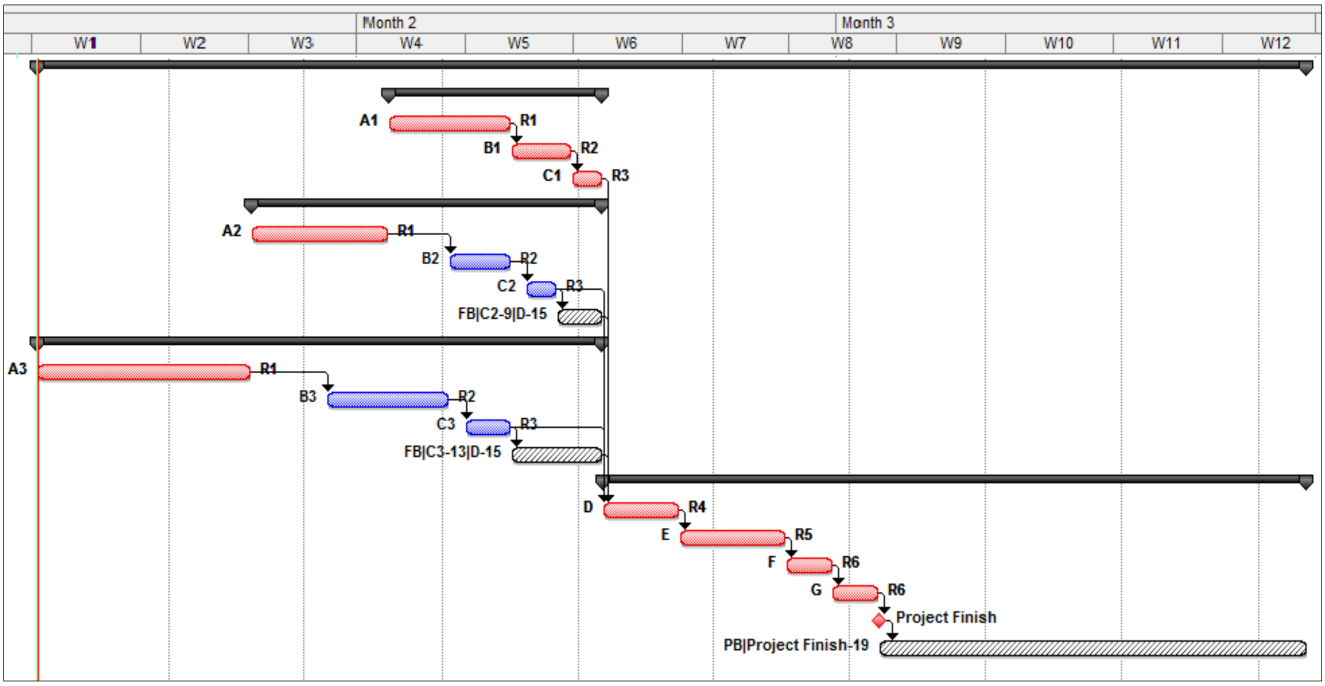

Figure 1. The Critical Chain Schedule. (Leach 2014).

5.2. MATHEMATICAL STATEMENT OF THE EXAMPLE PROBLEM

Let the first subscript associated with variables; for example, $X3_{A1}$ represents the variable belonging to the third discrete point "of activity (A1). SS_{A1} represents scheduled start variable of activity (A1). We have: No. of zero-one variables = 39, No. of activity scheduled start variables= 14, then the problem can be stated as:

Minimize: $100000X1_{A1}+105000X2_{A1}+110000X3_{A1}+82000X1_{B1}+86100X2_{B1}+90200X3_{B1}+60000X1_{C1}+63000X2_{C1}+$
$66000X3_{C1}+125000X1_{A2}+131250X2_{A2}+137500X3_{A2}+35000X1_{B2}+36750X2_{B2}+38500X3_{B2}+29000X1_{C2}+30450X2_{C2}+$
$31900X3_{C2}+225000X1_{A3}+236250X2_{A3}+247500X3_{A3}+42000X1_{B3}+44100X2_{B3}+46200X3_{B3}+36000X1_{C3}+37800X2_{C3}+$
$39600X3_{C3}+9600X1_{D}+12096X2_{D}+12672X3_{D}+24000X1_{E}+31015X2_{E}+36554X3_{E}+72000X1_{F}+100800X2_{F}+118800X3_{F}+$
$10000X1_{G}+14000X2_{G}+16500X3_{G}+5000SF$

Subject to:

$X1_{A1}+X2_{A1}+X3_{A1}=1$
$X1_{B1}+X2_{B1}+X3_{B1}=1$
$X1_{C1}+X2_{C1}+X3_{C1}=1$
$X1_{A2}+X2_{A2}+X3_{A2}=1$
$X1_{B2}+X2_{B2}+X3_{B2}=1$
$X1_{C2}+X2_{C2}+X3_{C2}=1$
$X1_{A3}+X2_{A3}+X3_{A3}=1$
$X1_{B3}+X2_{B3}+X3_{B3}=1$
$X1_{C3}+X2_{C3}+X3_{C3}=1$
$X1_{D}+X2_{D}+X3_{D}=1$
$X1_{E}+X2_{E}+X3_{E}=1$
$X1_{F}+X2_{F}+X3_{F}=1$
$X1_{G}+X2_{G}+X3_{G}=1$
$X1_{A1}+X1_{A2}+X1_{A3}=1$
$X2_{A1}+X2_{A2}+X2_{A3}=1$
$X3_{A1}+X3_{A2}+X3_{A3}=1$
$X1_{B1}+X1_{B2}+X1_{B3}=1$
$X2_{B1}+X2_{B2}+X3_{B3}=1$
$X3_{B1}+X3_{B2}+X3_{B3}=1$
$X1_{C1}+X1_{C2}+X1_{C3}=1$
$X2_{C1}+X2_{C2}+X2_{C3}=1$
$X3_{C1}+X3_{C2}+X3_{C3}=1$
$SS_{A1}+16X1_{A1}+16X2_{A1}+16X3_{A1}-SS_{B1}<=0$
$SS_{B1}+8X1_{B1}+8X2_{B1}+18X3_{B1}-SS_{C1}<=0$
$SS_{C1}+4X1_{C1}+4X2_{C1}+4X3_{C1}-SS_{D}<=0$
$SS_{A2}+17X1_{A2}+17X2_{A2}+17X3_{A2}-SS_{B2}<=0$
$SS_{B2}+8X1_{B2}+8X2_{B2}+18X3_{B2}-SS_{C2}<=0$
$SS_{C2}+4X1_{C2}+4X2_{C2}+4X3_{C2}-SS_{D}<=0$
$SS_{A3}+28X1_{A3}+28X2_{A3}+28X3_{A3}-SS_{B3}<=0$
$SS_{B3}+16X1_{B3}+16X2_{B3}+16X3_{B3}-SS_{C3}<=0$
$SS_{C3}+6X1_{C3}+6X2_{C3}+6X3_{C3}-SS_{D}<=0$
$SS_{D}+10X1_{D}+6X2_{D}+4X3_{D}-SS_{E}<=0$
$SS_{E}+13X1_{E}+8X2_{E}+6X3_{E}-SS_{F}<=0$
$SS_{F}+6X1_{F}+4X2_{F}+3X3_{F}-SS_{G}<=0$
$SS_{G}+6X1_{G}+4X2_{G}+32X3_{G}-SF<=0$

END

GIN $X1_{A1}$, $X2_{A1}$,…………….., $X3_{G}$,
GIN SS_{A1}, SS_{A2},………..…., SS_{G}

5.3 THE PROBLEM SOLUTION

Global optimal solution found where objective value is LE **1247776.** Project duration is equal to 70 days.

Table 2. Values of Model Variables for Most Economical Solution.

Variable	Value	Variable	Value	Variable	Value
X1A1	0.00	X2A1	0.00	X3A1	**1.00**
X1A2	0.00	X2A2	**1.00**	X3A2	0.00
X1A3	**1.00**	X2A3	0.00	X3A3	0.00
X1B1	0.00	X2 B1	**1.00**	X3 B1	0.00
X1B2	0.00	X2 B2	0.00	X3 B2	**1.00**
X1B3	**1.00**	X2B3	0.00	X3B3	0.00
X1C1	**1.00**	X2 C1	0.00	X3 C1	0.00
X1C2	0.00	X2 C2	0.00	X3 C2	**1.00**
X1C3	0.00	X2C3	**1.00**	X3C3	0.00
X1D	0.00	X2D	0.00	X3D	**1.00**
X1E	0.00	X2E	0.00	X3E	**1.00**
X1F	**1.00**	X2F	0.00	X3F	0.00
X1G	0.00	X2G	**1.00**	X3G	0.00
SF	70.00				

Table 2 shows that:-

1- Activities (A1, A2, and A3) started at the same date because they use the same resource but activity A1 will be executed in the third shift, activity A2 will be executed in the second shift, and activity A3 will be executed in the first shift.

2- Activities (B1, B2, and B3) started at the same date because they use the same resource but activity B1 will be executed in the second shift, activity B2 will be executed in the third shift, and activity B3 will be executed in the first shift.

3- Activities (C1, C2, and C3) started at the same date because they use the same resource but activity C1 will be executed in the first shift, activity C2 will be executed in the third shift, and activity C3 will be executed in the second shift.

4- Working in multiple shifts system and increasing labors wages in second and third shifts are a motivation for labors not to waste time and to concentrate on finishing activities in their time. So, multiple shifts can be used to overcome Student's Syndrome and Parkinson's Law

.**5-** Total project duration is minimized from 85 days to 70 days with 17.64% reduction in project normal duration.

VI. CASE STUDY

A case study of cable stayed bridge project as a part of national project (Rod El farag axis) is presented to validate the proposed model. The location of the project is in Giza government in Egypt. The length of the bridge is 540 meter and its wide is 66.8 meter. The project consists of two pylons at main axes (R2, R3), main span with length 300 meter and six side spans with length 40 meter for each span over the Nile River as shown in figure 2. The work in the project involves, mainly, piles works, foundations, and reinforced concrete works of pylon and side span, steel segments works for main span, preliminary tension of cables, precast concrete slabs, and final tension of cables. The part of the project that is made to apply the model in this study is consisted of pylon R2, three side spans between pylon R2 and axis R1 and half of main span with length 150 meter.

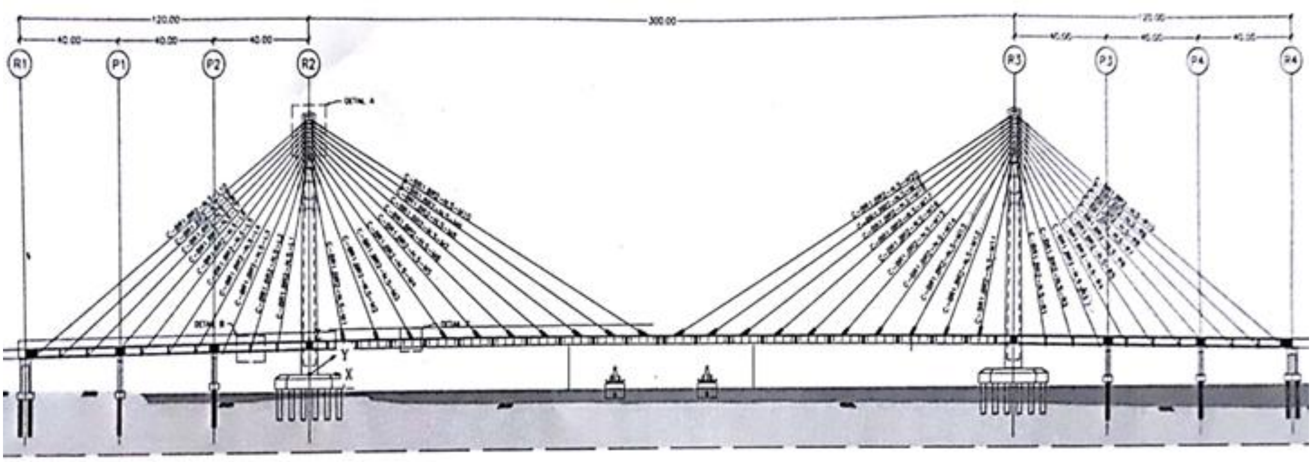

Figure 2. Layout of Cable Stayed Bridge. **(Elhosary 2019).**

6.1. Project Method Statement

The bridge deck is supported on two pylons R3 in the west, R2 in the east and six axes P1, P2 and R1 in the east and P3, P4 and R4 in the west. Each Main Bridge pylon is founded on 80 piles with 2m diameter, up to 48m depth. Each axis of P1, P2, P3, and P4 is founded on 38 piles with 1.5m diameter, up to 44m depth. Each axis of R1 and R4 is founded on 40 piles with 1.5m diameter, up to 44m depth. Piles works were carried out using drilling machines, floating rigs, barges, labors, and cranes. Metallic cantilevers and steel beams were carried out to consist a rigid base for reinforced concrete works for pile caps.

The pylons are consisted of three columns for each pylon. Each column is a box section. The outer dimension is 5.50 x 7.50 m. Each column is constructed on 20 stages. Each stage consists of steel fixing works, form works, placing works and striking form works. To complete work in each stage of columns, steel fixers, form workers, placing labors, helpers, barges, boom placer and tower crane are used. Two tower cranes were located on the pile cap next to the two outer columns of each pylon. Each tower crane worked with each outer column about 65% of stage duration and worked with internal column about 35% of stage duration. Other services cranes vary from 350 to 600 tons are used to help in completing different works in the project. The columns are linked by one cross tie beam at 14th stage to be worked as one column.

The structure of the deck is composed of 40 steel segments with 15 * 32 m dimensions for each segment and precast slab over each segment. Steel segments were fabricated at contractor workshops in Helwan city and then transported to site. Steel segments are preassembled in site yard by cranes vary from 350 to 600 tons. Steel segments are put on barges by cranes 600 tons, moved in the river then erected using derrick cranes with lifting beams and arranged in previous segment by welders and skilled labors. Steel segments were executed respectively.

The structure of the side span slab is box section and composed of two transverse concrete girders linked by four longitudinal concrete cross girders and two longitudinal edge beams in each direction. Cables are linked with main span and side span by anchors located every 15m to steel segments of main span and every 12m to the longitudinal edge beams of side span. Each column is linked by 10 cables with main span and 10 cables with side span by anchors of inner shuttering located every stage from stage 15 to stage 20. The 15th and 16th Stages contain one anchor for each stage and stages 17- 20 contain two anchors for each stage. Cables contain strands which vary from 51 to 110 strands in main span and 48 to 90 strands in side span. Cables are tensioned preliminary after segments erection and finally after erection of reinforced precast slabs. Tension equipment is used for preliminary and final tension of cables to make bridge balance. Electric works, barriers and asphalt works are constructed.

6.2. Project Utility Data

Utility data for activities contains its durations and the corresponding costs are given by (Elhosary 2019). The durations; (d), are given in days and the costs; (c), are given in Egyptian pound (LE). Indirect cost of the project is suggested to be LE 250000 per day. Normal duration of this part of the project considering all activities executed in only day shift is 1280 working days with total cost of (LE. 968,618,032). As built duration of this part of the project is 630 working days with total cost of (LE. 828,095,652), where all activities executed in triple shifts/ day.

6.3. Mathematical statement of the problem

The project is formulated for three cases (Elhosary 2019). Case (1) is formulated to optimize as built duration considering two tower cranes are used with columns of pylon R2 as constrained related activities. Steel segments are executed respectively. No. of zero-one variables = 466, No. of activity scheduled start variables= 194, and No. of constrained related activities variables= 57.

Case (2) is formulated considering execution of each two steel segments in parallel. Also, the three columns for each stage of pylon are considered as one activity with summation of costs and the longer duration of columns. No. of zero-one variables = 410. No. of activity scheduled start variables= 156. This case does not contain constrained related activities.

Case (3) is formulated considering two tower cranes are used with columns of pylon R2 as constrained related activities and each two steel segments executed in parallel. No. of zero-one variables = 466, No. of activity scheduled start variables= 194, and No. of constrained related activities variables= 57.

6.4. The problem solution

LINGO is used to handle the above optimization problem automatically by finding the answer that yields the best result. Global optimal solution for each case is found. Prochain scheduling software is used to implement critical chain scheduling for each case. Results of optimization solution for the three different cases and corresponding CCPM schedule solution are shown in table 3.

Table 3. Results of Optimization of different three Cases** (Elhosary 2019).

No.	Application Part Case	Duration (days)	% Decrease in normal duration	Total Cost (LE)	% Decrease in normal cost
1	CPM Schedule of Normal duration	1280	0%	968,618,032	0%
2	CPM Schedule of as built duration	630	50.78%	828,095,652	14.5%
3	Optimization Solution of case 1	630	50.78%	812,495,900	16.12%
4	CCPM Schedule of case 1 using Prochain	1119 days (771 days+ 348 days PB)	12.57%	Not Considered	
5	Optimization Solution of case 2	498	61.09%	781,308,400	19.34%
6	CCPM Schedule of case 2 using Prochain	1107 days (841 days+ 266 days PB)	13.51%	Not Considered	
7	Optimization Solution of case 3	507	60.4%	784,885,300	18.97%
8	CCPM Schedule of case 3 using Prochain	1067 days (800 days+ 267 days PB)	16.64%	Not Considered	

6.5. Discussion of results

Constrained related activities of columns for each pylon stage are considered for cases (1) and (3) in optimization solution by execution one, double or three shifts for each column. So, it is considered as most economical solution. Non-critical activities for three cases are scheduled in their early dates to avoid any delays in project completion date.

Results of case (1) show that the optimum project duration is 630 days at total cost of (LE. 812,495,900). The optimum project duration is decreased by 50.78% of normal project duration and it is equal as built duration. The optimum project cost is decreased by 16.12% of normal project cost. In contrast, critical chain project management method decrease project duration to 771 days and 348 days as project buffer with reduction of 12.57% of normal project duration.

Results of case (2) show that the optimum project duration is 498 days at total cost of (LE. 781,308,400). The optimum project duration is decreased by 61.09% of normal project duration. The optimum project cost is decreased by 19.34% of normal project cost. In contrast, critical chain project management method decreases project duration of this case to 841days and 266 days as project buffer with reduction of 13.51% of normal project duration.

Results of case (3) show that the optimum project duration is 507 days at total cost of (LE. 784,885,300). The optimum project duration is decreased by 60.4% of normal project duration. The optimum project cost is decreased by 18.97% of normal project cost. In contrast, critical chain project management method decreases project duration of this case to 800 days and 267 days as project buffer with reduction of 16.64% of normal project duration
The previous results prove that project duration can be minimized with minimum cost considering characteristics of construction projects regarding to activity discrete relationship between time and cost, multiple shifts and constrained related activities. In contrast, CCPM minimizes project duration without consideration of construction projects features and cost. Also previous results illustrate that non-critical activities are scheduled in their early start dates unlike critical chain method which scheduled non-critical activities as late as possible. Working with multiple shifts system and increasing labors wages in second and third shifts are a motivation for labors not to waste time and concentrate on finishing activities in their estimated durations. So, multiple shifts can be used to overcome Student's Syndrome and Parkinson's Law.

VII. SUMMARY AND CONCLUSION

In this paper, a brief review of CCPM and its requirements that do not satisfy construction projects are presented. The proposed model has been developed dealing with optimum duration with minimum cost of construction projects. The model is formulated using integer programming and utilization of multiple shifts for the activities and constrained related activities in construction projects. The model procedures and final solution of the case study for different cases show that multiple shifts and discrete relationship between activity time and cost are effective and can be applied on construction of mega projects. They express construction real-life characteristics and give optimal project duration with minimum cost. Multiple Shifts system is very useful to treat constrained related activities for execution of activities by the same machine. Working in shifts system makes labors to be keen to finish activities in time and prevents to a great extent loss of productivity. So, multiple shifts can be used to overcome Student's Syndrome and Parkinson's Law; principles of CCPM.

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