Vandana Publications
IJEMR

Volume-7, Issue-1, January-February 2017
International Journal of Engineering and Management Research
Page Number: 338-344

Critical Chain over Critical Path in Construction Projects

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ABSTRACT

The major constraints of any construction projects are time overruns, cost overruns, unavailability of resources when required, less productivity, incompletion of project within time and even sometimes projects stopped completely at the execution stage itself. It is necessary for the project managers to meet the project delivery date to satisfy the needs of the customers in the competitive world today. So, it becomes mandatory for a project to be planned and scheduled properly to deliver it on-time. This shows that the traditional critical path method which is being used nowadays to be ineffective. In order to create an effective and efficient scheduling method, Eliyahu M.Goldratt applied Theory of constraints (TOC) in project management and the outcome was a robust scheduling technique called critical chain project management (CCPM). In this paper, a real-time project is scheduled using both traditional CPM and emerging CCPM methods to identify the optimal scheduling technique for a construction project.

***Keywords*—** critical chain project management, critical path method, optimal scheduling, Theory of constraints.

I. INTRODUCTION

One of the serious issues due to which the on-time completion based upon a pre-determined schedule becomes a failure in many of the projects. According to many researches as of 1998, only 44% of projects typically finish on-time. Therefore, it is evident that there are notable limitations found with traditional project management methods like critical path method (CPM) and program evaluation and review technique (PERT). It is also unavoidable for the project managers to face uncertainties. Beyond considering task relationships alone among the tasks, it also necessitates a strong systematic method considering resource constraints and uncertain conditions in project scheduling in order to get a robust and reliable project. The limits in the traditional methods encouraged people to develop a new scheduling method called Critical Chain Project Management (CCPM).

CCPM is a method of planning and managing uncertainties in the projects that emphasizes resources to execute project tasks. Disseminating the concept of Theory of Constraints (TOC) into the project management provides an effective and efficient critical chain project management method. In the beginning, CCPM was popularly used in production systems only but now it is also available to the construction sectors.

1.1 What's problem with Traditional Scheduling methods?

1. Student syndrome (assumption of having more time to finish the task)
2. Parkinson's law (do not promote being early and tending to fill the complete time allotted)
3. Wasting extra safety time
4. Multi-tasking with same resource.
5. Path-merging (non-critical path merges with critical path)

1.2 How to solve the predicaments in traditional methods?

CCPM tries to find solutions to the issues in traditional method by the following ways.

1. Eliminating due-dates and milestones.
2. Providing realistic estimates of 50% level and not a negative approach of 90% level (viewing pessimistically that all tasks will finish late).
3. 'No blaming' culture.
4. Scheduling non-critical activities as-late-as possible (reduced work-in-progress and not incurring the costs earlier than necessary).

1.3 OBJECTIVE

The main objective of this paper is to bring the awareness to the people of construction sectors about the emerging CCPM techniques by bringing into light its advantages over the traditional CPM method by comparing both the methods using a real time case study.

Also the limitations of the current CCPM technique are also analyzed and the suggestions are given for the future work in this particular technique.

II. REVIEW OF LITERATURE

From the various literature reviews, the critiques of traditional project management method and the advent of critical chain project management method were studied in detail and both the methods were compared by applying them on a real life case study.

Goldratt (1997) first developed the managerial method of critical chain project management in his book 'The Goal' which described the concept of CCPM in a narrative fashion. The critical chain in CCPM is defined as the longest path considering both task and resource dependencies instead critical path in traditional critical path method is the longest path considering only task dependencies [2].

The project delays in traditional methods include the reasons like pessimistic approach in estimation of activity durations, negligence of variations in activities, merging of non-critical paths into critical path, loss of focus due to multitasking. Unlike traditional methods CCPM reduces the above constraints with the application of CCPM [4].

People think that when tasks start as soon as possible, it tends to finish more earlier, but the real fact is that when tasks start earlier, it leads to work-in-progress (WIP) of activities, causing idling of resources (men, materials and machineries) and ultimately increase the budget of the project. But in CCPM, the activities are scheduled for late-start (LS) to reduce WIP and to save cost [1].

The literatures also arrive at the fact that the uncertainties in the project are more when individual tasks are provided with the safety times. The uncertainties are found to be reduced in cases where safety times available to each individual task are aggregated at one particular point. The aggregated safety times is said to be buffers in CCPM technique [3].

2.1 PROJECT MANAGEMENT

A project is a temporary endeavor undertaken, to provide a service or product that has start and end times with well-defined scope, plan and resources.

A project management is the application of knowledge, skills, tools and techniques in a project to meet the project requirements [5].

2.2 THEORY OF CONSTRAINTS

Theory of constraints (TOC) is the root of the critical chain project management method and the term was first coined and used by Eliyahu M. Goldratt in his book 'The Goal' in 1984. He first applied TOC to production systems and it was later extended to the construction field. The basic concept of TOC is that there may be at least a single constraint available to each stage in a project and the performance of the project must be increased when those constraints are eliminated completely. Thus, significant measures are to be taken in optimizing the constraints of a project. To improve the outcome of the project, TOC focuses on the following five steps.

1. Identify the constraints.
2. Exploit the constraints.
3. Sub-ordinate everything else to the system.
4. Elevate the constraints.
5. Repeat the process from step 1, if there are further constraints in the system.

2.3 BUFFERS

The buffers are the aggregated safety times which are added to keep the project on-track. It is provided for the purpose of managing risks and delays in the particular project [5].

Project Buffer: A project buffer is inserted between the last task of a critical chain and the project completion date to protect the critical chain from delays.

Feeding Buffer: A feeding buffer is inserted after the last task of the non-critical chain in order to protect the critical chain from the merging of non-critical chains.

Resource Buffer: A resource buffer is provided for the critical chain activities in order to ensure that the resources are available to them when necessary.

III. METHODOLOGY

The paper compares CCPM method and the traditional CPM through a case study of construction of a residential building. The data is collected from a real-life project. The MS-Project software is used as a scheduling tool in the project.

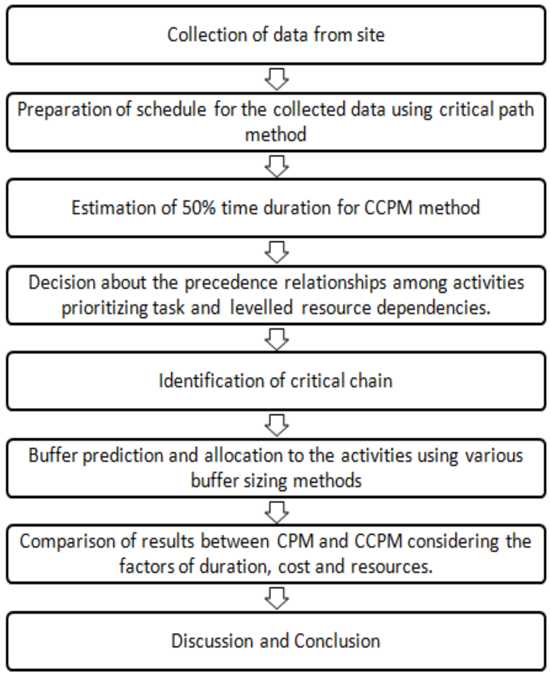

Figure.1 Methodology

The methodology of his paper is represented in figure.2. As per the above methodology, the activities of each task and buffers are figured out and it is reviewed with various literatures. From that, a clear picture of the concept of CCPM is attained.

The summary of buffer and its calculations is clearly arrived. After obtaining the result of CCPM, it is compared with the traditional method to find which is suitable to the field of construction.

IV. CONCEPTUAL FRAMEWORK AND BUFFER SIZING

4.1 TYPICAL OVERVIEW OF CPM

The overview of the critical path method of scheduling is seen with a case study of a residential building. The original schedule of the project done by CPM using MS Project software is shown in figure.2.

		Task Mode	Task Name	Duration	Start	Finish	Predecessors
0			**CONSTRUCTION OF A VILLA**	**76 days**	**Fri 05-04-13**	**Tue 02-07-13**	
1	✓		Earthwork Excavation for foundation in all soils	4 days	Fri 05-04-13	Tue 09-04-13	
2	✓		Sand filling for foundation and Basement with River sand	5 days	Sat 06-04-13	Thu 11-04-13	1SS+1 day
3			P.C.C 1:5:10 Mix concrete for foundation and curing works	10 days	Wed 10-04-13	Sat 20-04-13	2SS+3 days
4			Brickwork for foundation	3 days	Mon 15-04-13	Wed 17-04-13	3SS+4 days
5			R.C.C 1:2:4 Mix Concrete using for Plinth beam, Lintel Beam, Roof slab,and curing works	10 days	Thu 18-04-13	Mon 29-04-13	4
6			Reinforcement works	13 days	Wed 24-04-13	Wed 08-05-13	5SS+5 days
7			Brickwork for superstructure	8 days	Mon 29-04-13	Tue 07-05-13	5SS+9 days
8			Plastering in CM 1:4 using 12mm thick for all walls	15 days	Fri 03-05-13	Mon 20-05-13	7SS+4 days
9			Plastering in CM 1:3 using 20mm thick for ceiling	13 days	Wed 15-05-13	Wed 29-05-13	8SS+10 days
10			White wash one coat	7 days	Thu 23-05-13	Thu 30-05-13	9SS+7 days,8SS
11			Colour wash two coat including labour charges	8 days	Thu 30-05-13	Fri 07-06-13	10SS+2 days,9
12			Supplying and fixing patak wood doors and window fittings	15 days	Mon 03-06-13	Wed 19-06-13	11SS+3 days
13			Supplying and fixing marbles over a 1:5:10 concrete	8 days	Mon 03-06-13	Tue 11-06-13	11SS+3 days
14			Supplying and fixing for floor tiles	3 days	Thu 06-06-13	Sat 08-06-13	13SS+3 days
15			Supplying and fixing for wall tiles	8 days	Fri 07-06-13	Sat 15-06-13	14SS+1 day
16			Weathering course with lime mortar Brick Jelly over a R.C.C Roof	4 days	Fri 07-06-13	Tue 11-06-13	15SS
17			Supplying and Laying one coat of pressed tiles over W.C with lime mortar	3 days	Fri 07-06-13	Mon 10-06-13	16SS
18			Water supply, sanitary arrangements ,Electrification, front elevation works,etc.,	22 days	Fri 07-06-13	Tue 02-07-13	17SS
19			Finishing works	10 days	Wed 12-06-13	Sat 22-06-13	18SS+4 days

Figure.2 Original schedule using CPM

In CPM, the Work Breakdown Structure (WBS) is created which divides the entire project into individual tasks. The success of CPM depends on the sequence and inter-dependencies among activities with the proper utilization of resources. Although CPM holds a particular position in project management, people' faith towards it is reducing day-by-day.

The loss of popularity in critical path method may be due to the following disadvantages.

1. Without understanding the ultimate aim of project completion, people tend to increase additional safety times to each individual task in CPM.
2. People only focus on task dependencies and resource dependencies are not given preference in critical path analysis.
3. Critical paths may change at any stage of the project and there may be more than one critical path which leads to confusion.
4. During Execution, there may be more chance of non-critical paths becoming critical path.
5. The basic assumptions in CPM are far beyond the practical scenario and the project team's prediction of scope is not under control.

4.2 TYPICAL OVERVIEW OF CCPM

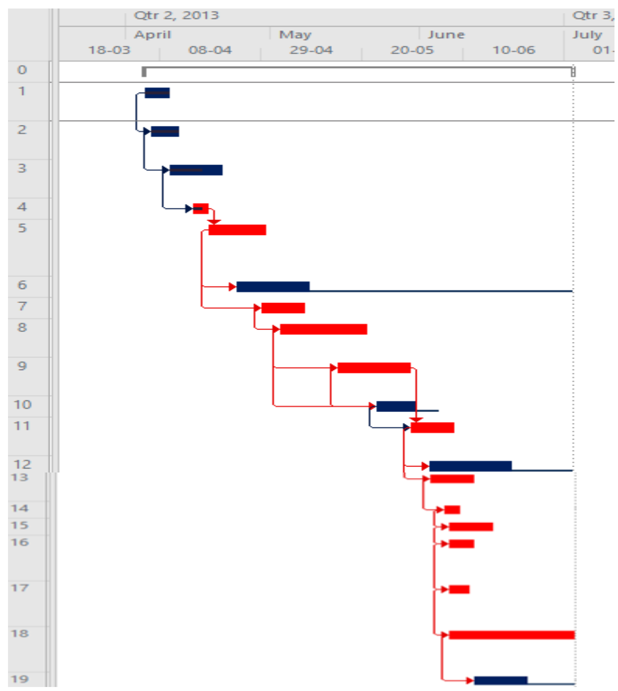

Figure.3 Gantt view of CPM

The following are the general steps followed in the critical chain project management technique.

1. The aggressive 50% time estimation is calculated for each for each activity.
2. Resources allocated separately to each activity and it must be leveled.

 ISSN (ONLINE): 2250-0758, ISSN (PRINT): 2394-6962

3. After Resource leveling, relationships between the activities are predicted incorporating both task dependencies and the leveled resources' dependencies.
4. The longest path of the activities including both tasks and resources is identified as a critical chain.
5. Rescheduling of the project is done to ensure that the critical chain remains the same for the entire project.
6. The project buffer is inserted at the end of the critical chain and feeding buffers are inserted at the end of each non-critical chain to prevent non-critical chains becoming critical chains. The buffers are calculated using various Buffer-sizing methods and the methods are discussed in detail in the upcoming steps.
7. Buffer Monitoring and Buffer Management are the immediate steps to be undertaken after completion of the buffer insertion process.
8. Proper Buffer sizing and Buffer Management processes leads the project o complete earlier as scheduled also achieves good results in terms of cost performance of the project.

4.3 PREVENTION OF UNCERTAINTIES

Uncertainties are the major factors found in the traditional methods and the critical path analysis is lagging in dealing with the uncertainties. These are the major problems to which the traditional methods cannot able to give solutions. But the CCPM method handles the uncertainties in a proper way to eradicate it completely.

a. Providing average and aggressive 50% duration estimations for activities.
b. Scheduling backwards instead of proceeding in forward direction from the project finish date using latest start.
c. Providing cumulative buffers to safeguard the project against uncertainties.
d. Using the buffer monitoring and buffer management concepts to track and control the project via the periodical review of it by analyzing how it varies with the original schedule and updating of the schedule based on the progress report of the project.
e. Risk management with the provision of fever charts.

The below figure shows the critical path with leveled resources. After assigning leveled resources to critical path it becomes critical chain. But duration is not yet updated according to CCPM method.

	ℹ	Task Mode	Task Name	Duration	Start	Finish	Predecessors	Resc Nan	Resourc materia	Un
0			CONSTRUCTION OF A VILLA	90 days	Fri 05-04-13	Thu 18-07-13				
1	✓		Earthwork Excavation for foundation in all soils	4 days	Fri 05-04-13	Tue 09-04-13		6	59.86	M3
2	✓		Sand filling for foundation and Basement with River sand	5 days	Sat 06-04-13	Thu 11-04-13	1SS+1 day	8	97.57	M3
3			P.C.C 1:5:10 Mix concrete for foundation and curing works	10 days	Wed 10-04-13	Sat 20-04-13	2SS+3 days	6	13.85	M3
4			Brickwork for foundation	3 days	Mon 15-04-13	Wed 17-04-13	3SS+4 days	5	30.59	M3
5			R.C.C 1:2:4 Mix Concrete using for Plinth beam, Lintel Beam, Roof slab,and curing works	10 days	Thu 18-04-13	Mon 29-04-13	4	7	27.92	M3
6			Reinforcement works	13 days	Wed 24-04-13	Wed 08-05-13	5SS+5 days	12	3629.60	KG
7			Brickwork for superstructure	8 days	Mon 29-04-13	Tue 07-05-13	5SS+9 days	8	50.66	M3
8			Plastering in CM 1:4 using 12mm thick for all walls	15 days	Fri 03-05-13	Mon 20-05-13	7SS+4 days	10	643.61	M2
9			Plastering in CM 1:3 using 20mm thick for ceiling	13 days	Tue 21-05-13	Tue 04-06-13	8SS+10 days	10	79.27	M2
10			White wash one coat	7 days	Wed 29-05-13	Wed 05-06-13	9SS+7 days,8SS-	11	722.83	M2
11			Colour wash two coat including labour charges	8 days	Thu 06-06-13	Fri 14-06-13	10SS+2 days,9	11	722.83	M2
12			Supplying and fixing patak wood doors and window fittings	15 days	Mon 10-06-13	Wed 26-06-13	11SS+3 days	10	34.87	M2
13			Supplying and fixing marbles over a 1:5:10 concrete	8 days	Mon 10-06-13	Tue 18-06-13	11SS+3 days	9	56.70	M2
14			Supplying and fixing for floor tiles	3 days	Thu 13-06-13	Sat 15-06-13	13SS+3 days	7	11.72	M2
15			Supplying and fixing for wall tiles	8 days	Fri 14-06-13	Sat 22-06-13	14SS+1 day	8	35.85	M2
16			Weathering course with lime mortar Brick Jelly over a R.C.C Roof	4 days	Fri 14-06-13	Tue 18-06-13	15SS	3	7.19	M3
17			Supplying and Laying one coat of pressed tiles over W.C with lime mortar	3 days	Fri 14-06-13	Mon 17-06-13	16SS	4	89.90	M2
18			Water supply, sanitary arrangements ,Electrification, front elevation works,etc.,	22 days	Mon 24-06-13	Thu 18-07-13	17SS	8		L.S
19			Finishing works	10 days	Fri 28-06-13	Tue 09-07-13	18SS+4 days	7		L.S

Figure.4 Highlighted critical and feeding chains in CCPM method

(where)

- critical chain
- feeding chain 1
- feeding chain 2
- feeding chain 3
- feeding chain 4
- feeding chain 5

The critical chain shown in the above figure.4 (4-5-7-8-9-11-13-14-15-16-17-18) is inserted with the project buffer after the last task 18.The feeding buffer 1 is inserted after the task 3, feeding buffer 2 is inserted after the task 6, feeding buffer 3 is inserted after the task 10, feeding buffer 4 is inserted after the task 12, feeding buffer 5 is inserted after the task 19. Let us see how the buffers are calculated using the sizing methods.

The necessary data required for buffer calculations are given in the following table.

Sl. No.	Activity	Original Duration	Aggressive duration	Standard deviation
1	A	4	2	0.5
2.	B	5	2.5	0.625
3.	C	10	5	1.25
4.	D	3	1.5	0.375
5.	E	10	5	1.25
6.	F	13	6.5	1.625
7.	G	8	4	1
8.	H	15	7.5	1.875
9.	I	13	6.5	1.625
10.	J	7	3.5	0.875
11.	K	8	4	1
12.	L	15	7.5	1.875
13.	M	8	4	1
14.	N	3	1.5	0.375
15.	O	8	4	1
16.	P	4	2	0.5
17.	Q	3	1.5	0.375
18.	R	22	11	2.75
19.	S	10	5	1.25

Table.1 Durations required in CCPM buffer calculation.

(where activities A- Earthwork Excavation for foundation in all soils, B- Sans filling for foundation and Basement with river sand, C= P.C.C…etc.,)

4.4 BUFFER SIZING METHODS

In critical chain project management method, the safety times are given in the name of buffers and there are different types of buffers used such as project buffer, feeding buffer(s) and resource buffers which were discussed earlier.

The buffers are sized using the following four types of buffer sizing methods.

1. cut and paste method
2. Root squares error method
3. Adaptive procedure with resource tightness
4. Adaptive procedure with density

4.4.1 CUT AND PASTE METHOD (C&PM)

This is the first proposed buffer sizing method by Eliyahu M. Goldratt in his book 'Critical chain' in the year 1997 which is the simplest of all the buffer sizing methods. It was named later as 'Cut and paste method' or '50% of the chain method' by other authors.

Here, the project buffer size is equal to half of the duration of the critical chain and the feeding buffer size is equal to half of the duration of the feeding or non-critical chains. Although this sizing method is very easy to calculate, it has limitations such as negligence of uncertainties present in the activities and also activities with long durations produce large buffers which ultimately lack optimization in buffer sizing in this method.

Project buffer = 52.5/2 =**26.25 days**
Feeding buffer1 = **4.75 days**
Feeding buffer2 =**3.25 days**
Feeding buffer3 = **1.75 days**
Feeding buffer4 = **3.75 days**
Feeding buffer5 = **2.5 days**

4.4.2 ROOT SQUARED ERROR METHOD (RSQ)

In this buffer sizing method, rather than using a simple thumb rule as in cut and paste method, it sizes buffers as the square root of the sum of the squares of the difference between original duration and the aggressive duration for each activity along the chain.

It is somewhat better than cut and paste method, but this method associates with limitation that the probability of duration is greater than 90% that probably undersize the buffers than required for the critical chains.

Project buffer = **17.87 days**
Feeding buffer1 = **5.94 days**
Feeding buffer2 = **6.5 days**
Feeding buffer3 = **3.5 days**
Feeding buffer4 = **7.5 days**
Feeding buffer5 = **5 days**

But for non-critical chains the feeding buffer is correspondingly increasing for lengthy chains, say for example in the above case feeding buffer 2 =6.5days and feeding buffer 4 = 7.5days creates idling of time resource as a single task in those feeding buffers not needs such a lengthy feeding buffer. This is the main disadvantage of this method. This undersized project buffer and over-sized feeding buffers leads to a project failure.

4.4.3 ADAPTIVE PROCEDURE WITH RESOURCE TIGHTNESS (APRT)

The buffer size in this sizing method is given as a product of a scaling factor 'K' based on resource compression rate and the standard deviation of the activities proceeding the buffer.

$$\text{Buffer size} = K \times \sigma$$

Where

K = (resource usage / resource availability)

Here, the central limit theorem is applied in the calculation of standard deviation of the chain, which highlights that the average duration of the path is equal to the sum of the average durations of the tasks which makes the chain. Also, the variation in the chain is equal to the sum of variations of the activities forming the chain. The square root of the variance gives the value of standard deviation.

Project buffer = **71.85 days**
Feeding buffer1 = **1.25 days**
Feeding buffer2 = **1.625 days**
Feeding buffer3 = **1.4 day**
Feeding buffer4 = **1.875 days**
Feeding buffer5 = **1.25 days**

4.4.4 ADAPTIVE PROCEDURE WITH DENSITY (APD)

This buffer sizing method suggests the concept that when the number of precedence relationships among the activities increases then simultaneously the delays in the project also get increase (i.e.) the interdependence between the tasks is directly proportional to the delays occur in the project. The density of the project is nothing but the number of precedence relationships in the project. The significant factor in the buffer sizing method is the term 'density'.

Also the buffer size depends on a scaling factor 'K' which is set as one plus the ratio of total number of precedence relationships of the particular chain to the total number of tasks originally present in the same chain. The buffer size is the product of scaling factor 'K' and standard deviation of the activities preceding the chain.

$$\text{Buffer size} = K \times \sigma$$

Where

K=1+ (number of precedence relationships/total number of tasks)

Project buffer = **19.89 days**
Feeding buffer1 = **2.09 days**
Feeding buffer2 = **1.625 days**
Feeding buffer3 = **0.875 day**
Feeding buffer4 = **1.875 days**
Feeding buffer5 = **1.25 days**

4.4.5 MONITORING AND MANAGEMENT OF BUFFERS

In CCPM method, the project is not monitored according to its completion date instead it is monitored based on the rate of consumption of buffers by the activities.

The below are the three steps to be followed in buffer management on a periodic basis.

1. The size of the buffers should be adequately and appropriately arrived using efficient buffer sizing methods.
2. Buffer consumption rate should be predicted on a regular basis for the smooth progress of the project.

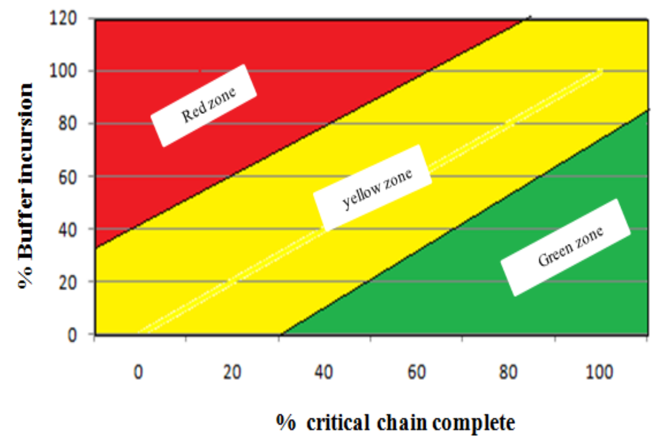

Figure.5 Fever charts

3. The above color-coded fever charts should be prepared which represent the risk-level in execution of the project through progress report according to which the buffers have to be managed on a weekly or monthly basis.

The color-coded signals represent the following.

Green zone = comfort zone – no action needed.

Yellow zone = warning zone – The main cause of the delay should be identified and action plan is to be prepared.

Red zone = risky zone – The activities should be started right now and corrective actions must be taken immediately.

4.5 SUMMARY

Buffers	C&PM	RSQ	APRT	APD
	(in days)			
Project Buffer	26.25	17.87	71.85	19.89
Feeding Buffer 1	4.75	5.94	1.25	2.09
Feeding Buffer 2	3.25	6.5	1.625	1.625
Feeding Buffer 3	1.75	3.5	0.875	0.875
Feeding Buffer 4	3.75	7.5	1.875	1.875
Feeding Buffer 5	2.5	5	1.25	1.25

Table.2 Project and feeding buffers calculated using four types of buffer sizing methods.

4.6 RESULT

The following table shows the total duration of the project using CPM and CCPM (APD) methods.

Sl.No.	CPM	CCPM			
		C&PM	RSQ	APRT	APD
	(in days)				

Total Project Duration	90	78.75	70.37	124.35	72.39

Table.3 Total duration of the project using CPM and CCPM methods

From the above results, it is understood that the CCPM works better than CPM in terms of both duration and cost of the project. But, in particular among the four different methods, Adaptive procedure with density (APD) of CCPM method proves to be the effective method because comparing the results of all four methods of CCPM, Root squared Error method gives the less duration of 70.37 days, but this method is not incorporating the factor of uncertainty into account and so the result is not accurate. Next to RSQ method, APD method is found to be giving lesser duration incorporating the factor of uncertainty and so the result must be accurate and closer to the real time scenario. Thus, implementation of CCPM method with APD buffer sizing method to a project might give an effective result by enhancing the planning and execution stages of a project to meet successful on-time completion within allocated budget.

V. CONCLUSION

It is experimentally observed that CCPM works better than traditional methods. Project completion date is prevented from uncertainties because of the use of fever charts as it helps the managers to take protective actions against delays. It is known from literature reviews that CCPM has been extensively used in software and production firms. It is also recommended to the construction sectors to get benefit from CCPM approach.

It is clearly shown that the project might surely completed on-time as scheduled and also within the allotted budget as because the leveling and balancing of resources are done in CCPM before assigning precedence relationships among the activities, which paves way for the elimination of idling of resources.

The following advantages are noticed with CCPM method.

1. It accumulates all safety buffers at the end of the project instead of providing them into each activity, and protects the critical chain against insecurity.
2. It focuses on the project constraint (the longest chain of dependent resources or activities).
3. Uses average-case estimates (task estimates based on 50% probability of completion.
4. Starts tasks as soon as predecessors are done, finishes tasks as quickly as Possible
5. Avoidance of Student’s syndrome, Parkinson’s law, Murphy’s law, and Multitasking
6. Relay race Scheduling and Late start Scheduling of Non-critical activities.
7. No rescheduling and thus less work-in-progress
8. More chance of finishing on-time.

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