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Applications of Critical Chain Project Management and Buffer Sizing for Elevated Corridor Metro Rail Project

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Abstract: Critical Chain Project Management (CCPM) as a new concept originated at mid nineties and principally it had to take a long-term change in management perspective to adopt the unacceptable of past. In traditional project management language, the structure of a critical chain is similar to that of a "resource constrained critical path." Thus CCPM has been based and developed on the principles of Theory of Constraints (TOC). One of the main challenges of the CCPM is the adequate sizing of the time buffers. If the buffers were dimensioned beyond the necessary size, immediate practical implications happen. On the other hand, if buffers were underestimated it may increase the probability of duration overruns, which can represent financial penalties and reliable loss from the part of the customer or market. This paper is an attempt to apply the concepts and to explore the advantages of application of CCPM to a complex mega infrastructure project like construction of an elevated corridor for metro rail operations and also to compute the buffer size by some of the available methods. According to the sample analysis, it has been observed that the 'Sum of Squares Method' gives the maximum size of the buffer and the '50% method' gives the minimum buffer size. Also application of CCPM may result in a reduction of the over all duration of the project by about 3%.

Keywords: Critical chain project management; Theory of constraints; Metro rail construction; Buffer sizing.

I. INTRODUCTION

Critical chain project management (CCPM), in the largest sense, is the set of processes and practices for project management developed by the application of the Theory of constraints (TOC). This is also a thinking process to overcome the difficulties faced in delivering projects with both speed and reliability. The "body of knowledge" associated with critical chain centers on critical chain scheduling and buffer management for individual projects, and synchronization of efforts across projects in multi-project organizations. The critical chain of a project is the set of dependent tasks that define the expected lower limit of a project's possible lead time. Dependencies used to determine the critical chain include both logical hand-off dependencies (where the output of the predecessor task is required to start the successor), and resource dependencies (where a task has to wait for a resource to finish work on another task). The identification of the critical chain uses a network of tasks with "aggressive but achievable" estimates that is first "resource leveled" against a finite set of resources. In traditional project management language, the structure of a critical chain is similar to that of a "resource constrained critical path."

II. LITERATURE REVIEW

Goldratt (1997) first published the concept of CCPM. Like several of his prior texts, the book outlined the concept in a narrative fashion and does not seem to have been intended to be a "how-to" manual for CCPM. Rather, its purpose seems to have been to provide a basis for a stream of research that might be pursued by him and others. Goldratt (2000) developed on his first CCPM model by describing in details about the "Haystack Syndrome" Pittman (1994) and Walker (1998) examined the single and multiple project environments (respectively) and sought to expose the assumptions and practice of scheduling and controlling projects by traditional methods. Hoel and Taylor (1999) sought to provide a method (via simulation) for determining the appropriate size for the buffers required by CCPM.

Rand (2000) introduced CCPM to the project management literature framing CCPM as an extension of TOC. He concluded that CCPM not only dealt with the technical aspects of project management (like PERT/CPM) but also that CCPM dealt with how senior management manages human behavior in the construction of the project network as well as the execution of the network. Steyn (2000) followed this research with an investigation of the fundamentals of CCPM.

He concluded that a major impediment to implementing CCPM is that it requires a fundamental change in the way project management is approached and that such a change is likely to meet with resistance. Further, Steyn (2004) worked primarily with the principles of 'Theory of constraints (TOC)' which can be considered as the basic principles towards application and development of a CCPM model.

III.CONCEPTUAL FRAMEWORK AND BUFFER SIZING

One of the main challenges of the CCPM is the adequate sizing of the time buffers. If the buffers were dimensioned beyond the necessary size, immediate practical implications happen, for example: unnecessary addition of costs and/or anticipated investments or eventual losses of market chances. On the other hand, if buffers were underestimated it may increase the probability of duration overruns, which can represent financial penalties and reliable loss from the part of the customer or market.
If buffers are adequately sized, the project conclusion date should be satisfied and rarely exceeded. However, in both cases the size of the project buffer can depend on the desired probability for completing the project schedule and should be determined according to it.
After the Goldratt's (1997) proposal of the critical chain principles of scheduling and management for projects, several authors suggested different methods for sizing projects and feeding buffers, which will be presented and discussed in the following section.

A. 50% Method
Goldratt (1997) suggested a practical and simple cut of 50% in the pessimistic duration (Tp) and to schedule a buffer of 50% of the trimmed duration of the chain with (n) activities. Variations of the method have been used considering 50% of the sum of the differences between a tendency measure (Tm) and the estimated pessimistic duration of the chain activities (n) as

$$\mathrm{BfS} = 0.5\sum_{i=0}^{n}(\mathrm{Tp}-\mathrm{Tm}) \quad (1)$$

Where BfS is Buffer size.
Tp is Pessimistic duration and
Tm is Central Tendency measure of distribution.

Equation (1) permits the consideration of the asymmetry of the underlying variability in activity. The advantage of this approach is its intrinsic simplicity, which, although fully in line with the CCPM approach, tends to over-estimate project duration so resulting in a less competitive bid.

B. Root Square Error Method
New bold (1998) detailed and developed the Goldratt's critical chain concepts and launched two other classical methods. New bold (1998) revealed the approximated formula (2) assuming lognormal distributions functions for activity duration with mean (μ) and pessimistic durations, (Tp).

$$\mathrm{BfS} = \sqrt[2]{\sum_{i=0}^{n}[\tfrac{\mathrm{Tp}-\mu}{2}]^2} \quad (2)$$

Where BfS is Buffer size.
Tp is Pessimistic duration and
μ is mean of distribution.

This method seeks to define the buffer in terms of the risk associated to the chain. Assuming the realistic hypothesis that the duration of the activities has a lognormal distribution, two estimates are required for the duration of each activity: the first (Tp) is the safe option and must include a margin of error to compensate delays, the second (μ) does not include a margin of error. The author suggests calculating the two estimates using a 85 percentile and the median of the distribution. The difference between the two values (D = (Tp) - (μ)) is proportional to the variability in duration of the activity. There is then a series of suggestions to refine the use of this methodology.

C. Simulation Method
Schuyler (2001) proposed this method is based on the Monte Carlo simulation technique and requires the knowledge of the duration distribution, along with its median and variance, for each project activity.

Project execution is simulated obtaining the distribution of the project duration taking account of the possible impact of sub-critical chains. The size of the project buffer depends on the required probability of completing the project within the agreed date. It is determined as:

$$\mathrm{BfS} = q_{85\%} - q_{50\%} \quad (3)$$

Where BfS is Buffer size.
$q_{85\%}$ is 85 percentile of distribution and
$q_{50\%}$ is median of the distribution.

Where $q_{85\%}$ corresponds to the a percentile of the total duration of an activity excluding special causes of delay typically, while $q_{50\%}$ is the median of the distribution, following Goldratt, (1997)

D. The Classes of Uncertainty Method
Shou and Yeo (2000) suggest that all activities should be placed into one of four classifications, which they arbitrarily designate A, B, C, and D. A is said to have a very low level of uncertainty, B is said to have a low level of uncertainty, C is said to have a high level of uncertainty, and D a very high level of uncertainty.

The authors suggest that the activities be classified based on their 'relative dispersion (RD_i), which is obtained from the average duration (μ) and the standard deviation (σ) of each activity, as:

$$\mathrm{RD}_i = \frac{\sigma}{\mu} \quad (4)$$

Where RD_i is relative dispersion of activity duration estimation.
σ is Standard deviation of distribution.
μ is mean of distribution.

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The method proposes a sub-division into four classes of uncertainty (very low, low, high, very high), one of which is associated to each activity. For each class, there are three percentage values representing the desired safety level (low, medium, high) which, when multiplied by the duration of the activity, return the margin of protection. The sum of the margins of protection of the activities in the chain gives the size of the buffer protecting the chain. Furthermore, this method requires a large amount of data.

Table 1. Class Uncertainty Margin of Protection Matrix

Class Uncertainty margin of protection Matrix				
RD_i Range	Classification	Low safety	Medium safety	High safety
< 0.25	A	4%	8%	12%
0.25-0.50	B	12%	24%	36%
0.50-0.75	C	40%	60%	80%
> 0.75	D	28%	57%	85%

IV. CASE STUDY AND ANALYSIS

A case study based methodology is adopted for this research; where in the primary data have been taken from study of ongoing Bangalore Metro Rail Corporation Ltd (BMRCL) (reach -3) elevated corridor construction. The data collected pertains to construction activities of segmental construction and its related aspects. The construction activities have been taken for only reach-3 which is first phase of project. The critical path method (CPM) and CCPM method were used to find out the duration of a sample stretch considering sub activities. The data pertaining to duration in construction activities of the elevated corridor metro rail project has been collected from documented evidences and observation. In addition to this, 6 major activities were selected for further analysis and also data were collected based on relationship of different activities of construction of elevated corridor for metro rail construction. This data is analyzed to find out the relationship of different activities as well as risk in each activity. The route alignment has been chosen to serve high population density areas of the city with connectivity to the heart of the city where the central business district (CBD) and the seat of the Government are located and has been suitably integrated with the existing railway and bus systems. About 40 % of the route is on curves (including transition curves). Minimum radius of curve on elevated section is 120 m to reduce property acquisition. However minimum radius of 300 m is adopted in underground sections to facilitate working of tunnel boring machines. Stations are provided on straight stretch, as far as possible. However some stations are provided on curves but limiting the radius to 1000 m so that the gap between the train and the platform is kept within the prescribed dimension. Most of the alignment is kept as elevated to minimize land acquisition and its cost. Length of underground sections is restricted to congested areas where elevated construction is not feasible. On the east - west corridor the elevated stretches are from Mysore Road terminal to Magadi Road - Tank Bund Road junction near Subhash Nagar and from Chinnaswamy stadium to Baiyappanahalli station. The underground stretch is from Subhash Nagar to the end of Cubbon Park. Baiyappanahalli station is on the surface. On the north - south corridor, the elevated stretches are from Yeshwantapur to Swastik and from K R road to R V Road terminal. Swastik station is at grade while the underground stretch is from Swastik to City Market station. The break-up of route length for the elevated and the underground sections is given below:

Table 2. Reach 3 Route Details of BMRCL

S No.	Station name	Chainage (Km)	Type of Construction
1	Yeshwantapur	0.000	Elevated Corridor.
2	Soap Factory	1.150	Elevated Corridor.
3	Mahalaxmi	2.102	Elevated Corridor.
4	Rajaji Nagar	3.069	Elevated Corridor.
5	Kuvempu	3.975	Elevated Corridor.
6	Malleswaram	4.728	Elevated Corridor.
7	Swastik	5.858	Elevated Corridor.
8	Majestic	7.540	Underground

From the case study done at Reach-3 of BMRCL, it is been found that the viaduct construction follows a linear production model of activities namely,

1. Piling.
2. Pile Cap casting.
3. Pier Casting.
4. Pier Cap Casting.
5. Casting of Segments.
6. Launching Of Segments.

For simulation method, required cumulative percentile is found by running 1000 iterations of beta PERT samples in Monte Carlo simulation with the help of Risk Amp software. For the simulations input data is calculated from a sample size of 30 nos observed at site. The durations as computed from the observed data in presented in Table 3.

Table 3. CCPM Duration for Piling Activity

Duration Calculation in Days			
1	Standard Deviation.(σi)	SD	1.00
	Average (μ)	Mean	2.03
	Central Tendency (T)	Median	2.00
	Most Likely Duration.(Tm)	Mode	1
	Optimistic Duration(To)	Min	1

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	Pesimistic Duration(Tp)	Max	4
2	Critical Path Duration(Tm)		1.50
3	Critical Chain Duration		
	a. 50% Method		
	(Tp / 2)+∑(Tp-Tm)/2		2.50
	b. Sum Of Squares Method.		
	(Tp / 2)+√(∑((Tp- µ)/2)2)		4.69
	c. Simulation Method		
	$q_{85\%}$ / $q_{50\%}$	BfS %	
	2.03 / 1.49	27%	
	(Tp x BfS %) + (Tp / 2)		3.08
	d. Class Uncertainty Method.		
	Rdi = (σi) /(µ)	0.49	
	Safety Percentage.%	36%	
	(Tp x SP %) + (Tp / 2)		3.44

From the data collected, parameters listed under item no 1(σi, µ, T, Tm, To , Tp and Tm) is derived from the data observed at site, from a sample size of 30 nos. For calculating duration of activity for CCPM, 50% method (Tp / 2)+∑(Tp-Tm) /2 is used. The buffer size BfS = ∑((Tp-Tm)/2)= 0.50 and activity duration including buffer size is calculated as (Tp / 2)+ BfS = (4/2) + 0.50= 2.50 days. For calculating duration of activity for CCPM, Sum Of Squares Method (Tp / 2) + $\sqrt{\sum((Tp-\mu)/2)^2}$ is used .Where in buffer size BfS = $\sqrt{\sum((Tp-\mu)/2)^2}$ = 2.69 and activity duration including buffer size is calculated as (Tp / 2)+ BfS = (4/2)+2.69= 4.69 days.

For calculating duration of activity for CCPM by Simulation Method the equation used is (Tp x BfS) +(Tp / 2) .The buffer size is BfS = (Tp x BfS %) = 1.07 and activity duration including buffer size is calculated as (Tp / 2)+ BfS = (4/2) + 1.07= 3.08 days.

For calculating duration of activity for CCPM by Class Uncertainty Method, the equation used is (Tp x SP%) + (Tp / 2) . Where in buffer size BfS = (Tp x SP%) = 1.44 (SP% derived as 36% from table no 1(Class Uncertainty Matrix) by substituting coefficient of variation (Rdi = (σi) /(µ)) of sample under study and safety required from site observation.) and activity duration including buffer size is calculated as (Tp / 2)+ BfS = (4/2) + 1.44= 3.44 days.

Extracting results from all the above steps, Critical Chain Schedule model for a two spans of BMRCL Reach-3 has been developed in self contained optimized method with Project Scheduler-8 software containing 640 activities with two point time estimate. For the analysis purpose the same sample project is also prepared in PERT format and duration of the project is found out as below.

Table 4: Computation of duration reduction through CCPM

Method Used	Start date	End date	Duration (working days)
Critical Chain Method	12th March 2011	22nd June 2011	102
Critical Path Method	14th March 2011	27th June 2011	105
Percentage reduction in duration = 2.85%			

On developing both the schedules, calendar is set as 12 hr working days (4 hrs overtime) with a 7 day working week. The most critical task, i.e. in terms of financial risk; the launching of segments is kept in continues running. All the preceding activities are optimized to take maximum output from constrained resource (launching girder). The sample schedule can be further up scaled by introduction of more constrained resources and subsequently adding supporting resources. The percentage deduction in duration is calculated as (105-102)/105= 2.85%.

V. CONCLUSION

This seminal research results show the potential benefit of CCPM methodology based on buffer strategies can produce an unprecedented level of optimization in resources, production throughput, with certainty in complex infrastructure projects like construction of elevated corridor for metro rail operations. The use of a real case to test the proposed CCPM methodology shows the feasibility to apply it within the construction scheduling context in repetitive projects. As a part of sample analysis it has been observed that for piling activity by '50% method', the buffer size as computed is 2.50days. By 'Sum of Squares Method' the buffer size is 4.69 days. By 'Simulation method' the computed buffer size is 3.08 days. Finally by 'Class Uncertainty Method' the size of buffer is 3.44 days. Thus, according to the sample analysis, the 'Sum of Squares Method' gives the maximum size of the buffer and the '50% method' gives the minimum buffer size. In simulation method of buffer sizing for the major activities of the project, by running 1000 iterations, it's been found out that piling activity needs maximum buffer size of 27% and segment launching activity needs minimum buffer size of 10%. Also, it has been observed from this study that critical path duration of 105 days can be brought down to 102 days;a reduction of 2.85%, is achievable in project in planning stage. Multitasking was reduced to 0%, due to the iterative process of eliminating multitasking process before buffer placing process. As a scope of future study a detailed CCPM model can be developed based on TOC, and the developed model can be applied to on-going projects and future metro rail projects in India and abroad. Further, as the concept is generic, the same concept can be applied to other complex mega infrastructure projects.

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BIOGRAPHIES

Dr. Debasis Sarkar has graduated in Civil Engineering from Bangalore University, India in 1996, received M. Tech in Building Science & Construction Management from Indian Institute of Technology, Delhi in 2001 and Ph.D in Project Management from D. D University, India 2009.

He is presently Associate Professor and Head at Dept. of Civil Engineering, Infrastructure Engineering & Management Programme, School of Technology, Pandit Deendayal Petroleum University, Gandhinagar, Gujarat, India. He has about seven years of industrial and about thirteen years of academic experience. He was also employed as senior engineer and site incharge with Delhi metro rail project. He has published about 34 research papers in peer reviewed international and national journals. His research interest includes project management, risk management, metro rail construction technologies, other advanced construction technologies, green building materials and technologies, statistical quality control, ready mixed concrete and value engineering.

Dr. Sarkar is life member of Institute of Engineers India and annual member of Indian Roads Congress. He is also the editorial board member of a number of peer reviewed international journals.
Robin Babu completed his M. Tech in Construction and Project Management from CEPT University Ahmedabad. He was also PMP from Project Management Institute, India. He was working with JLL, a renowned project management consultancy organization. Unfortunately, due to cardiac failure, he expired in 2016.