Critical Chain Project Management- A Critique

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ABSTRACT

Theory of Constraints in Goldratt's international best seller "The Goal" identified the Critical Chain as "The sequence of dependent events that prevents the project from completing in a shorter interval. Resource dependencies determine the critical chain as much as do task dependencies." Such a criterion derived the salient notion of the Critical Chain Project Management (CCM). This approach was advocated to compete with the Critical Path Method (CPM). In this paper, an in-depth review is performed to outline the main Pros and Cons of CCM and a comparative scheme is made among the refinements proposed by various investigators with a focus on buffer sizing. A light is then shed on such practice in Location-Based Scheduling (LBS) on the local region with emphasis to national projects. The New Suez Canal project is selected as a case study for applying CCM. Based on stochastic approach, the current study finally presumes the Best Unbiased Logical Estimate (BLUE) for buffer distribution in Location-Based Scheduling that provides a reliable guideline for sizing process with acceptable confidence level.

Keywords: Project management, Critical Chain; Critical Path Method, Time Buffers; Theory of Constraints; Location-Based Scheduling.

1. INTODUCTION

The Critical Path Method (CPM) constitutes the predominant technique for planning and scheduling of construction projects since late 1950s. CPM besides Gantt charts, which was introduced by Gantt and Taylor in the early 1900, provides the common corner stone in scheduling tools [10]. In CPM the activities are the units of analysis containing the data needed for tasks description along the project. Activities can be treated as deterministic units included in a logical network for the calculation of the minimum duration to complete the network of activities. If, on the other hand, the activities are treated from a probabilistic perspective, a Program Evaluation and Review Technique (PERT methodology is used to assess the likelihood and risk of the activities to be completed on a determined date. With the help of simulation methods as Monte Carlo, all the activities of the network can be integrated and the total duration of the project estimated.

Although CPM has proven to be a very powerful technique for planning, scheduling and controlling projects, especially for complex and non-repetitive work [1], it does not directly allow form an aging and monitoring resource limitations [2]. Repetitive activities are often characterized by imbalanced production rates that might lead to unforeseen work stoppages and, consequently, inefficient resource usage [23]. In CPM that assumes unlimited resources available for executing the work, the activities and their logical connections, are the principal focus, whereas resources are given minor attention. Consequently, CPM-based schedules, may result in discontinuous resource usage that in turn will lead to interruptions in the production where each trade suffers from recurrent starts and stops during the project process. It is difficult to monitor the planned resource usage from a Gantt chart, as the different amounts of work and different pace of each trade is concealed in the bars of the activities.

As construction work maybe generally characterized by continuous or repetitive work, where the same activities are executed at various locations of a building or construction, construction scheduling appears to be more closely aligned to repetitive scheduling methods such as “Line-of-balance”, “Time-location Matrix Model”, “Construction Planning Technique”, “Time Space Scheduling method”, “Flow-Line” and similar methods [1, 10, 13, 17] which were referred to as “linear scheduling methods” or “repetitive scheduling method” since those methods have proven to be well suited for projects of a repetitive nature. It was agreed that the linear or repetitive scheduling methods strongly suggest locations or places and, consequently, the comprehensive term of “location-based scheduling” (LBS) was proposed [10]. However, despite the long history and a promising potential of these repetitive, linear or location-based scheduling methods, they have gained little attention among the practitioners of the construction industry.

On the other hand, the original technique of CCM planning and project management is simple compared to many alternative techniques, such as simulation, quantitative risk assessment, PERT three time estimates, or Monte Carlo methods [17]. The primary concepts are simple; comprising 50/50 estimates, the critical chain, buffers, and buffer management. CCM requires neither statistical sophistication nor possession of actual distributions of activity performance data. Such data usually does not exist for projects, and even where it does exist, such as in the construction industry, it has not solved the problem of time overruns.

Theory of Constraints of Goldratt [6, 7] ended with five focusing steps, which are applicable to any physical system: 1. "*identify*" the system constraint, 2. "*exploit*" the system constraint, 3. "*subordinate*" everything else to the system constraint, 4. "*elevate*" the system constraint, and 5. if, in the previous step, a new constraint has been uncovered, repeat the process. "*do not let inertia become*" the system constraint. This identified the constraint of a project as the Critical Chain, or “The sequence of dependent events that prevents the project from completing in a shorter interval. Resource dependencies determine the critical chain as much as do task dependencies.” Such a criterion derived the salient notion of the Critical Chain Project Management (CCM). This approach was advocated to compete with the Critical Path Method (CPM). Critical Path project planning has an often hidden assumption that an acceptable way to account for potential resource constraints on the project is to first identify the critical path, and then perform resource leveling [11, 12]. However, the early CCM suggested estimating activity durations to their 50% probability of being completed on time and consider a buffer (project and feeding buffers) at the end of each chain of activities to allow for uncertainties [2]. There are also some other buffers, namely resource buffer, drum buffer, capacity buffer and cost buffer. Some other characteristics are that it was completely against multitasking, did not consider activity due dates and schedules non-constraint activities to their latest start.

CCM is claimed not to be a holistic approach towards managing projects and is more a scheduling method addressing schedule-related aspects of projects [1]. Since the introduction of CCM in 1997 [2], it became the center of a controversy between Goldratt and his proponents and some academics who believed that the CCM principles are not novel to project management [8, 9, 11, 14, 16, 19]. On the other hand, Rolf [17] successfully considered applying critical chain buffer management theory in Location-Based scheduling. This technique is evolving year after another, with documented success stories in some of the biggest multinational companies in the world [1, 10].

The present paper addresses a comparison between CCM versus CPM. Selection of time buffer in Location-Based Scheduling (LBS) is discussed from the viewpoints of buffers sorts, buffer sizing besides the issues of simple or complicated monitoring, rescheduling, multitasking and multi-project management. Local and regional practices are considered and particularly in Egypt and Saudi-Arabia. The New Suez Canal project is further considered as a case study. Finally, a stochastic selection of time buffer is proposed.

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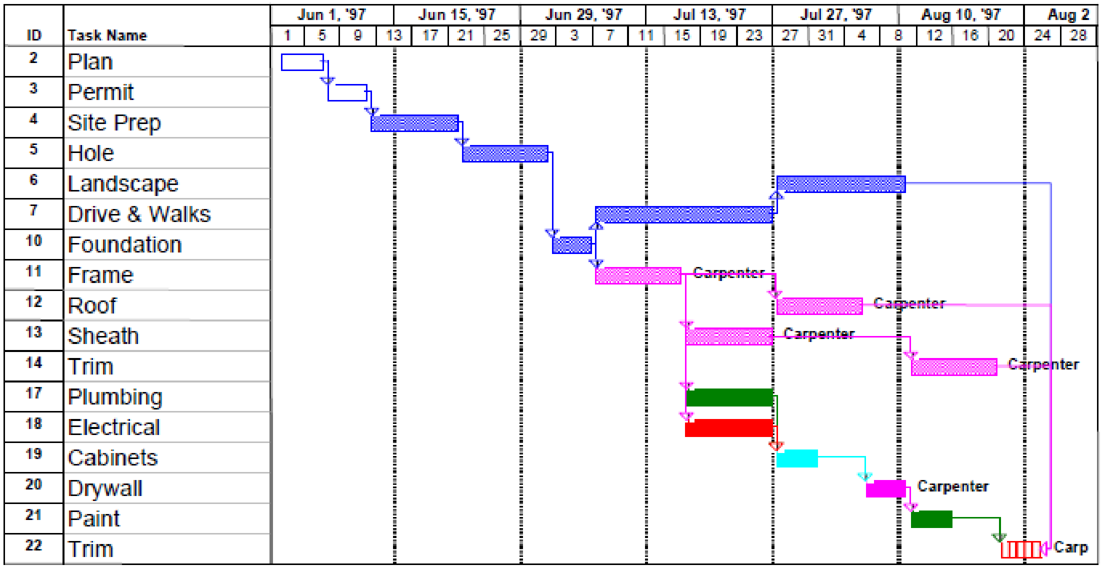
2. CRITICAL CHAIN METHOD (CCM) VERSUS CRITICAL PATH METHOD (CPM)

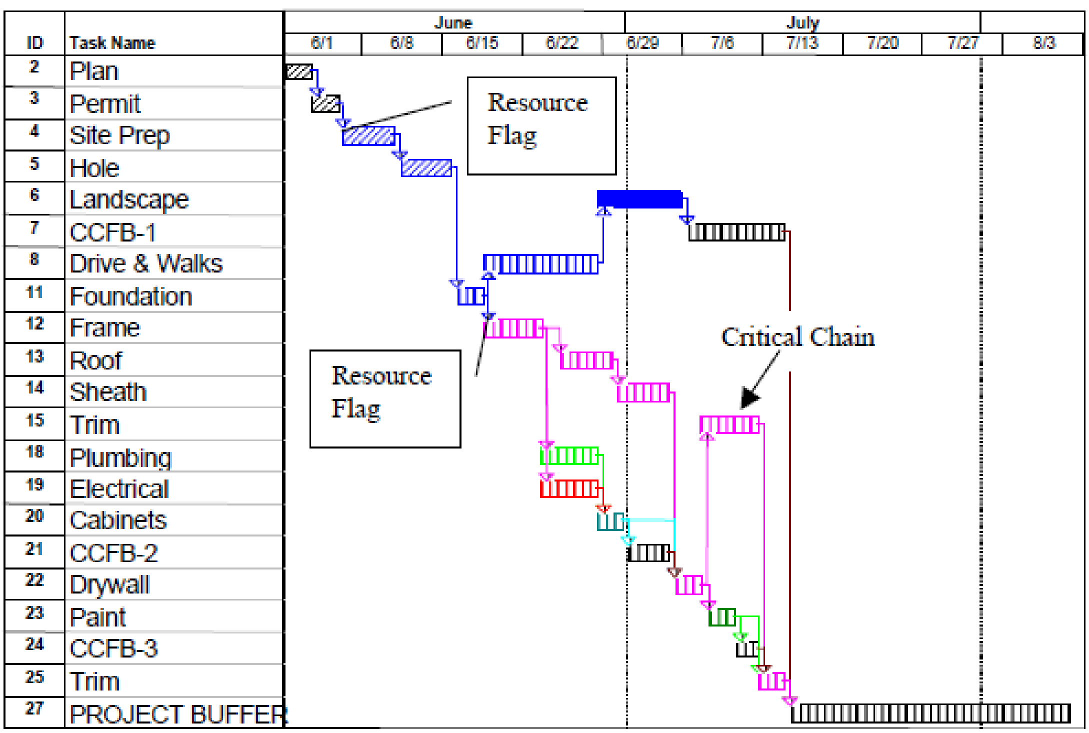
Fig. 1 illustrates a typical deterministic project schedule studied by Leach [12] where the colors represent unique resources. The plan identified the last activity as a critical path activity. Resource leveling has eliminated the rest of the critical path as a frequent result of resource leveling methods. Since the resource constraint is often a significant project constraint, the Theory of Constraints method of project planning always considers it and thus, the critical chain includes the resource dependencies that define the overall longest path (constraint) of the project. The method resolves all resource constraints while determining the project critical chain. The project critical chain may have gaps between activities. The improvements that result from CCM do not depend on having significant resource constraints or conflicts in the project. They apply to any project, for the reasons outlined below. For a project without resource constraints, the critical chain will be the same initial activity path as the critical path as shown in Fig,1.b. CCM differs from the critical path by:

a) Including resource dependencies, and
b) Never changing.

CCM improves the project plan by ensuring that it is feasible and immune from reasonable common cause variation (uncertainty, or statistical fluctuations). It does this by aggregating uncertainty into buffers at the end of activity paths. The Project Buffer protects the overall project completion on the critical chain path, and Feeding Buffers protect the critical chain from path merging. Buffer Management enhances measurement and decision making for project control. CCM implements required changes in resource behaviors, including elimination of date-driven activity performance and multitasking. Projects that use CCM have a greatly improved record of schedule, cost, and scope performance as they normally complete in less than one half of the time of projects using particular planning and control methods.CCM accounts for common cause variation as an essential element of the project management system. The process removes identifiable special causes of variation, including resource unavailability. CCM Project Managers use resource flags to identify and ensure availability of resources on the critical chain.



a. Example resource leveled critical path schedule.



- CCFB: Critical Chain Feeding Buffer

b. Example Critical Chain schedule identifies key features of the plan.

Fig.1: Comparative schedule by CPM and CCM [12].

3. SELECTION OF TIME BUFFER IN LOCATION-BASED SCHEDULING (LBS)

Many studies were conducted to characterize suitable time buffer system [2, 4, 12, 15, 21, 22, 24, 25]. Lumsden[13]used buffers to protect the continuous workflow and defined for the line-of-balance scheduling: stage buffers and activity buffers. Fig. 2 depicts the various sorts of buffers interventions. The stage buffers are used between major stages in projects to protect against unforeseen events such as weather. For example in tight sites where mobilization of particular equipment requires demobilization of some of unused existing equipment stage buffers become helpful. Activity buffers are applied to each activity to protect against minor incidents and fluctuations in productivity. The activity time buffers are not supposed to absorb major recurrent faulty productivity estimates. Lumsden[13] argued that the cost of buffers is low compared to the cost impact on the project if multiple activities are affected by delays. Kenley[10] stated that LBS emphasized the minimization of disturbances by allowing activity buffers and creating collective activities. CCM suggests estimating tasks to their 50% probability of on-time completion in order to exploit the constraint (critical chain) [7]. This has become a very controversial issue within the CCM debate.

Raz et al [16] argued that considerable safety times within activity durations were not always included. They concluded from a case study that the estimators did not overestimate noticeably. However, a weakness of this judgment was the lack of consideration of the CCM rationale for 50% probability estimation. Contrary to what Raz et al. [16] deduced, the original study proved that the large safety times included in the task durations were not being used to deliver activities earlier and still a noticeable percentage of them were being completed late. In another study, Herroelen and Leus[8] raised the same issue and stated that there are many people who underestimated the time of their allocated tasks because of their high confidence in completing them on time. With half of the tasks predicted to be delayed, CCM includes a reasonable safety time for different types of estimations (overestimation and underestimation) and different levels of activity risks [12].

Resource buffers are the alarms that are triggered by the tasks approaching their start time on the critical chain. They inform the resource allocated to a specific critical task of the time the resource should be ready to begin working on that activity. Raz et al. [13] also added that this type of buffers caused a disorganized environment and did not enhance the previous method of exposing the project schedule to all project team members. Moreover, Herroelen and Leus[8] mentioned the weakness of resource buffers to address the situation when two equal resources were able to perform a task.

CCM separates the safety times from the median task time and aggregates them after each chain of activities under the name of project buffer after the critical chain and feeding buffer after each chain of non-critical activities [12]. In order to shorten the project duration, these aggregated contingencies must be shorter than when they were calculated as part of the task durations. Goldratt[7] simply suggests deducting 50% of the safety times based on the 50% probability of task estimations where at least half of them are expected to be completed on time. Herroelen and Leus[8] explained the problem by asserting that Goldratt's method of buffer sizing was linear and buffer sizes constantly increased as time increased. They showed that using the 50% buffer sizing method could lead to unnecessary long project durations. The choice of linear construction projects that are characterized by their repetitive nature should come as no surprise. Goldratt's theory of constraints, that is the theory upon which the CCM method is founded, was developed for managing repetitive production systems [13]. Another reason is that, in more complex construction projects, it is typical to see paths splitting and merging again at various intermediate points. The resulting maze of paths in the network will make is difficult, if not impossible, to estimate the buffers, especially the feeding buffers. One ought In conclusion, the majority of survey participants expected *partial* success for the CCM scheduling technique in construction. None of those in management roles agreed to implement it immediately, but rather preferred to wait until implemented by others in the industry [5].

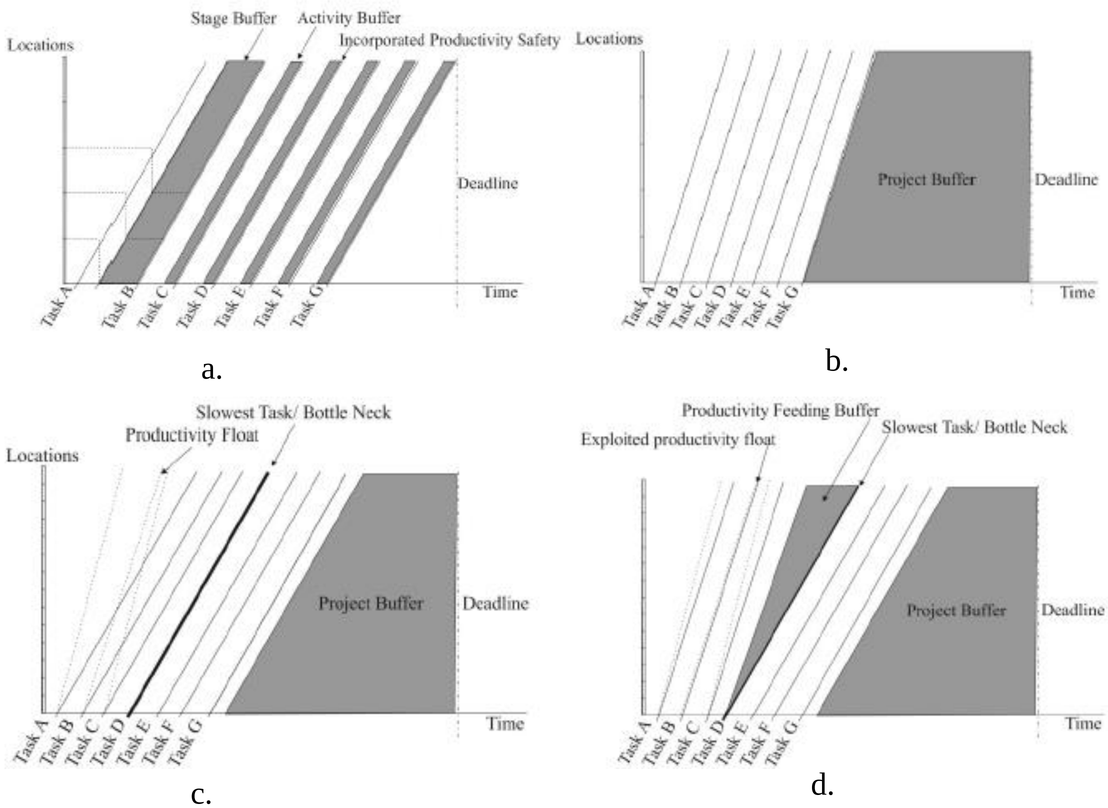


Fig. 2: Methods of distributing time buffers [17]

Project monitoring in CCM is conducted by measuring the level of feeding and project buffers' penetration during the project. Some authors have identified this as an advantage of CCM because of its simplicity compared to traditional methods [4, 12]. However, some others show that buffer consumption monitoring is a complicated function in large projects [13,23]. CCM does not allow multitasking in general but Herroelen and Leus[4] claimed that multitasking did not cause negative effects all the time and keeping employees under stress to complete a single task earlier can destroy morale. In contrast to traditional project management methods, CCM allows for multi-project management since the iterative nature of CCM (5-step process) can ensure the consideration of other resources. Herroelen and Leus[8] claimed that emphasis on rescheduling prohibition might be the reason for CCM not being appreciated in new product development projects where reiteration of project stages necessitates rescheduling. The unavoidable changes in the projected CCM schedule without showing buffers and gaps in the network was in fact a type of project rescheduling that was being undertaken in CCM. Ghaffari et al. [3] indicated that while the selected critical chain using both activity precedence and resource dependencies, the buffers were only based on the duration of their preceding chain of activities. The critical chain might alter during the project execution due to the difference in principles of determining the critical chain and the buffers.

It is argued that LBS projects should avoid applying stage buffers and weather contingency [17], should apply activity buffers to sensitive critical tasks, and should exploit productivity float in front of the slowest tasks, leaving the project buffer predominant [16].Placing a stage buffer after each month contradicts the recommendations of CCM, which say that the buffer will tend to be consumed by procrastination, and there will be little incentive to secure early finishes and build a buffer. Collecting the buffer at the end of a project should ensure that the buffer is only consumed if a delay does occur, and not due to procrastination. However, the project management refused to place the buffers at the end of the project. The scheduler wanted to incorporate and distribute the buffer across the project. By distributing the buffer to each month, the control schedule will communicate that the project is close to the plan. The actual performance will appear worse if the buffers are collected at the end.

4. Local and Regional Practices

As per the summary of the survey by George et al. [5], listed in Table 1,CCM faces many problems to consider it as a viable planning tool including lack of experience, not specifying it in contracts, unsuitability in complex projects and software changes besides need for training practitioners and convincing top management. About 10% and 44% of the surveyed industry professionals in Egypt and Saudi Arabia, respectively, had the opinion that CCM adds no real value in project planning despite the new scheduling approach used. Also, it is to be noted that the durations in CCM is frequently called Aggressive But Achievable Durations (ABAD).They see that using ABAD has a counterpart in CPM schedules via utilizing aggressive activity durations. And then, having a buffer between the planned end date and deadline for completion is not atypical. Construction professionals appreciated CCM as a new and innovative approach, nonetheless. Yet, the majority of the surveyed professionals (68% and 62% in Egypt and Saudi Arabia, respectively) believed it was applicable in construction industry under certain circumstances/constraints.

As per Table 1, there was a complete rejection of applying the 50% rule in construction practices. All considered it to be unrealistic due to the nature of construction activities. Construction professionals in Egypt were divided as to which is the better approach for estimating ABAD and the buffer, where approximately half opted for expert judgment and the other half preferred using analytical means to make the estimate. For the surveys in Saudi Arabia, there were more tendencies to use expert judgment as the primary basis for the estimates. The surveyed professionals conveyed an important point; that is ABAD estimation is a main challenge for CCM applicability in practice. The investigation of the project type(s) most suitable for the CCM implementation in construction industry, professional in Egypt and Saudi Arabia preferred linear projects, e.g., pipeline/utility projects, over the traditional building counterparts.

Table 1: Comparison of Regional Practices of CCM [5]

Component	Item	Egyptian Practice	Saudi Practice
Major obstacles to CCM application	Lack of experience	3%	18%
	Not specified in Contracts	18%	10%
	Unsuitability in complex projects	20%	12%
	Software changes	7%	13%
Method of buffersizing	50% rule	0%	0%
	Expert judgment	56%	74%
	Analytical/statistical means	44%	26%
Application of CCM	Building construction	26%	19%
	Linear projects (e.g. pipelines, utilities, etc.)	32%	37%

5. CSAE STUDY: THE NEW SUEZ CANAL CORRIDOR AREA PROJECT [20]

The New Suez Canal Corridor Area Project is a mega project in Egypt that was launched on 5 August 2014 for increasing the role of the Suez Canal region in international trading and to develop the three canal cities. It includes building a new city (new Ismailliah city), an industrial zone, fish farms, completing the technology valley, building 7 new tunnels between Sinai and Ismailliah and Port Said, improving 5 existing ports, and digging a new canal parallel to the Suez Canal. The new canal increases the canal capacity by allowing ships to sail into both directions at the same time for a greater proportion of the canal. The project will transfer the canal cities into an important trading center globally. It will also build new centers on the Suez Canal for logistic and ship services.

The New Suez Canal allows ships to sail to both directions in the same time. This will decrease waiting hours from 18 to 11 hours for most ships. The New Suez Canal will be 72 km long, including 35 km of dry digging, and 37 km (23 mi) of "expansion and deep digging".

The government will build 18 new factories in the industrial zone which will include: glass factory, car assembling factory, electronics factory, medicines factory, textiles factory, furniture factory, paper factory, sugar factory, food factory, petrochemicals factory, petrol refining factory, light metal manufacturing factory, and a minerals factory. Ship factories and services will be built among the Suez Canal corridor which includes: catering and services center for ships, ship manufacturing and repair center, a center for manufacturing and repairing containers, and logistic redistribution centers.

The new fish farms will be built in the eastern side of the Suez Canal. 23 tanks that will cover 120 square km with depth of 3-5m will cover the area from southern Tafrea to the gulf of Suez. This project is designed to produce high quality fish food. the project also includes building a solar panel that will produce Up to 2500 megawatts and reforming 400,000 acres of land in northern Sinai into farming land using the El-salam canal

Western Port-said Port lies on the northern entrance of the Suez Canal and is considered one of the most important ports in Egypt because of its location on the entrance of the Suez Canal. The port covers an area of 2.9 square km (the land area is 1.2 square km and the remaining 1.7 square km is water area). The port contains 37 docks which includes docks for passengers, yachts, and general goods. The port is divided into stations and each station contains a number of docks with its own working area (that includes repairing centers, equipment center, and stores). The maximum capacity of the port is 12 million tons yearly.

Eastern Port-said Port lies on the north western entrance of the Suez Canal branch which is a unique location because it connects 3 continents. The design of the port is geometrically ideal. The port was built in 2004 to serve international trading and act as a transit center between the continents. The port borders the Mediterranean Sea from the north, the industrial zone from the south, the salty lakes from the east, and the Suez Canal branch from the west. The port covers an area of 35 square km. The port authority plans to build docks the will reach 12 km long and an industrial zone south of the port covering 78 square km. Three stages are still remaining to fully complete and improve the port:

- Stage one is creating 8 stations with docks 8 km long
- Stage two is creating 15 station with docks 16 km long
- Stage three is creating 21 stations with docks 25 km long

El-Sokhna Port lies on the southern entrance of the Suez Canal.The port serves the oil and gas fields in the region. It exports products from the petrochemicals and refining factories in Ein al

Sokhna region. It also exports the products of a ceramic factory, ammonia factory, and a sugar factory.The port's total size is 24,919,337.85 square m:

- 3,400,000 square m is the water area
- 21,519,337 square m is the land area
- 1,000,000 square m is the Customs center
- The largest dock's size is 7 km long and 5.5 km wide

Arish Port lies on the Mediterranean Sea on the northern coast of Arish city and was transformedin1996 from a fishing port to a trading ships port. The port contains a dock which is 242m long that can serve huge ships. There is another dock which is 122m long that serves smaller ships. The port also includes covered storage areas which cover 2 square km and non-covered storage areas which cover more than 2.7 square km. On 5 June 2014 the port was no longer controlled by the Port Said port authority, the Ministry of Defence took control of it due to its sensitive location. The port contains a lighthouse that can be seen from up to 18 miles. The main importance of the port is that it exports Sinai products to the Mediterranean countries. The new projects include:

- Build a 2 km dock which will include containers station and a general goods station
- Build new storage areas
- Build a dock for yachts
- Build new logistic centers

El-Adabiya Port lies on the western side of the Suez Canal, about 17 km from Suez city. The Red Sea Ports Authority in Egypt controls the port. El-Adabiya Port consists of 9 docks which reach 1840m long and 42–27 foot deep. The water area is about 158 square km (which is also shared with the Suez Canal port and Petroleum Dock port) and the land area is 0.8 square km. The maximum carrying capacity of the port reaches 6.7 million tons yearly.

The construction of the new canal, which was scheduled to take three years, was instead ordered by the President to be completed in a year. Of course, CCM along with LBS was essential to manage the crashed time schedule. The tasks included the following:

- Task I: Dry Excavation phase in about 86 locations. The work gave the opportunity of 44,000 citizens to work with the help of 4500 equipment. A total of 84 companies, 2 armed forces troops for mine removal, 2 other troops to help in excavation. This was executed in 9 months with more than 250 million cubic meters of sand. The following activity was lining of the sides and embankments for longer than 100 km. Earth moving system with trucks was employed.
- Task II: Wet Dredging phase to approach the required design depth. This phase involved 2000 workers from the Suez Canal Authority, 3750 other workers with the help of 45 dredging equipment. This task included 4 floating lodges for the workers in various shifts. More than 258 million cubic meters of saturated and wet sand were removed. Earth moving system with trucks was employed.
- Task III: Construction phase for 120 buoy (shamendorah) along the naval route with solar lighting and connected to computerized system of the guiding centers including 10 new centers. Safety work was executed in this phase.

Project buffers were the main in this project no other types of buffers at all. Several contingency plans were prepared to avoid any likelihood of delay. Scheduling schemes are discussed in more details hereafter. The other components of the mega projects are planned to be scheduled in a similar manner.

According to the available data [20], Table 2 provides the characteristic durations of each task of the new Suez Canal phase. Values of a, b, and m are the main durations for β-distribution that are accustomed for PERT analysis described as the optimistic activity duration, the pessimistic activity duration, and the most likely activity duration, respectively. It has to be pointed out that more resources were mandatory to achieve the all crashed activities (a-values). The initial work plan for the three years schedule, Fig 3 illustrates the main activities. It can be noted that the b values have been assigned for durations for such long term plan.

Table 2: The characteristic durations of each activity

Task	β- distribution durations (days)		
	a	m	b
Dry Excavation	250	500	700
Wet Dredging	250	500	700
Pitching	200	300	500
Buoy Construction	200	300	500

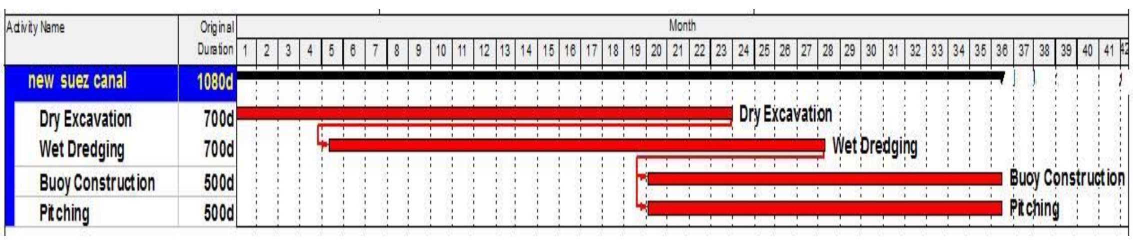


Fig. 3: The initial work plan for the three years schedule

With reference to the presidential order to shorten the project time to one year, the schedule was reconsidered with two years project buffer as shown in Fig. 4. This was more than the Goldratt's 50% probability crash in CCM. The fourth and fifth constraints of his theory [6, 7]were essential to provide this schedule; namely "*elevate*" the system constraint and if a new constraint has been uncovered, repeat the process. Of course, this necessitated careful work assignments in each location as the canal length was subdivided among more companies. In addition, earth moving system was important not to hinder mobilization and demobilization of equipment to the sites. Also maintaining safety of the sides of the original canal was a serious condition for location of tangency with the new route.

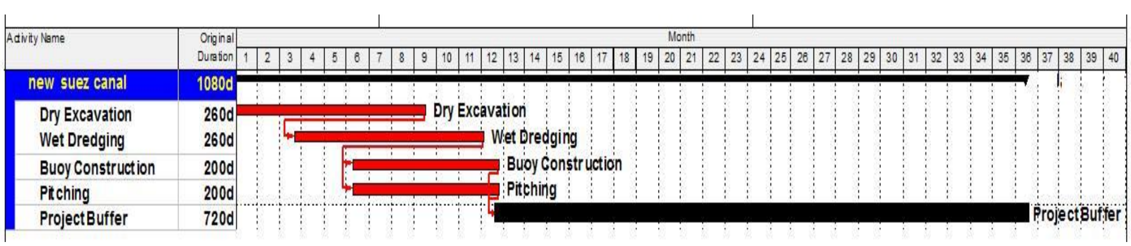


Fig. 4: The proposed work plan for the one year schedule

6.Proposed Stochastic Selection of Time Buffer

In view of the previous critique along with statistical background that the activity time ranges between two limits: optimistic and pessimistic, the following assumptions may be the basis to a logical distribution of the time buffer in CCM related to LBS, including:

- Most projects have multiple activity paths and all activity paths must merge into the critical path by the end of the project; if for no other reason into a milestone that identifies project completion. Usually, the path merges tend to concentrate near the end of the project. One reason for this is that 'assembly' or 'operations tend to occur near the end of the project, requiring many elements to come together. Activity path merging creates a filter that eliminates positive fluctuations, and passes on the longest delay. The reason is that merging activity paths means that all of the feeding paths are required to start the successor activity. Therefore, the successor activity can not start until the latest of the merging activities completes.
- The central limit theorem states that "as sample size increases, the distribution of the sample mean becomes closer to the normal distribution." Many project activities have a skewed probability distribution. That is, they have an absolute minimum time, and a long tail to the right meaning that they can take much longer than the average time [17]. These left skewed distributions also generally have a mean that exceeds the most frequent, or median/mean time. A project chain of activities is therefore more likely to have a symmetrical distribution, and a variance that is much smaller than the algebraic sum of the individual activity distributions. This is true whether the real distributions are known or not. CCM exploits the statistical law of aggregation by protecting the project from common cause uncertainty of the individual activities in an activity path with buffers at the end of the path. Buffers appear as activities in the project plan, but have no work assigned to them.
  - The total time that can be crashed within the project life is total buffer, TB, will be the summation of the difference between scheduled activity duration, D_i, and the optimistic duraction, OT_i(=a in β-distribution) , for each activity, I, on the critical crashed path.

    $$TB= \sum_{i}^{np} (D_i-OT_i)$$

    Where: n_p is the number of activities on the critical path of the crashed schedule.
  - Based on the crashed schedule, tasks are categorized and a LBS is conducted.
  - Activity buffers, AB, are essential items as crashed schedule is considered and a tendency to the mean time, MT_i (=m for β-distribution), of each activity is inherent in execution.

    $$AB= \sum_{i}^{np} \langle (D_i-MT_i) \rangle$$

    Where <> is Macaulay bracket whose value is zero when negative value is obtained. The mean time may be expressed for β-distribution as follows

    $$Mt_i=\tfrac{1}{6}(OT_i+4D_i+PT_I)$$

    Where PT_i (=b inβ-distribution)is the pessimistic duration of the I^{th} activity.
- The statistical methods to combine variances mean that you can protect a chain of activities to the same level of probability with much less total contingency time than you can protect each individual activity. For example, with a normal statistical distribution one standard deviation represents 67% of the data, or a cumulative probability that 67% of the time a result will fall within one standard deviation of the mean. Aggregation of the contingency times dramatically reduces the overall estimated time for a chain of activities. Therefore, only two third the activity

buffers may be assumed adequate for distribution after tasks whose duration are greater than their median. The rest of the activity buffer will be lumped to the project buffer.

- Project buffer, PB, is the main protection against the project delay and can be estimated as

$$PB=TB-\tfrac{2}{3}AB-RB-SB$$

Where RB and SB are the resource and the stage buffer, respectively.

- Eliminate, as possible, resource buffers, RB, except for essential circumstances of already anticipated delayed procurements or delivery. Also project driven supply chain may require this type of buffer [25].
- Stage buffers, SB, may be placed between major tasks for unforeseen situations but should be limited as possible.
- Productivity feeding buffers, PB, may be minimized by adopting similar production rates of the tasks and therefore the term slowest task mayvanish.CCM protects the critical chain from potential delays by subordinating critical chain feeding paths; placing an aggregated feeding buffer on each path that feeds the critical chain. This includes paths that merge with the critical chain at the end of the project. The feeding buffer provides a measurement and control mechanism to protect the critical chain.

The aforementioned procedure provides a rigorous, yet simple, statistically sound basis for distributing the time buffer through various components. It provides the Best Logical Unbiased Estimate (BLUE) for the buffer sizing and allocation. Further studies are needed to give a comparative study for this proposal in real life applications. This will give more reliable tool rather than the 50% rule and intuitive expert judgments.

Implementation of proposed (BLUE) procedure for case study of the new Suez Canal enabled a further (20 days) additional buffer for the one year work planas shown in Fig. 5. As a matter of fact this schedule was the closest to the real execution time table. This meant that the BLUE procedure can be very realistic for practical applications.

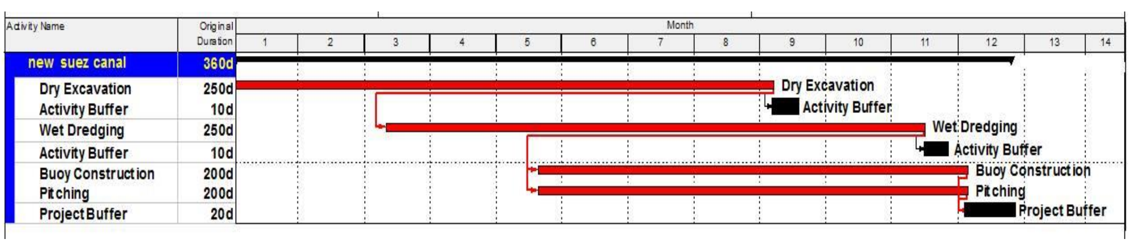


Fig. 5: Schedule with the proposed BLUE procedure for the case study

7. Conclusion

From the present investigation, the following conclusion may be drawn:

1. Critical chain project management is a viable tool for LBS.
2. The original concept is based on the Theory of Constraints advocated by Goldratt but faced several criticisms.
3. Discrepancies are still debatable regarding buffer sizing and allocation.

4. CCM is still limited for project management applications in the regional zone but proved superiority in the Egyptian mega project of New Suez Canal Corridor Area.
5. The proposed BLUE procedure, on statistical basis, enables reliable buffer estimation and distribution into project, activity, resource, stage and productivity feeding buffers, respectively.

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