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EFFICIENT PROCEDURE TO SCHEDULING CONSTRUCTION PROJECTS AT THE PLANNING PHASE

Matiwos TSEGAYE

Amhara Construction Design and Supervision Enterprise, Bahirdar, Ethiopia
Corresponding author's e-mail: matiwostse@gmail.com

Abstract. The construction industry is one of the most important activities that contributes towards the economic growth of any nation. However, the sector has been experiencing problems of cost and time overruns, particularly the problems are significant for the lowest-bid awarded construction projects in the developing countries where inappropriate planning is reported to be one of the major causes. Thus, the paper aims at developing an integrated scheduling approach for construction projects during the planning phase from a project owner's perspective. The proposed approach integrates cost estimation and schedule in light of practical activity precedence and mathematical cost optimization using different project commencement dates. The study has shown that cost and time optimization model could yield impractical results unless double precedence relations (start-to-start plus finish-to-finish) are imposed between some activities such as trench excavation and pipe laying. It has also demonstrated that the cost and time budgeted during the planning phase would substantially deviate from actual if the planned construction start date slips from the plan, particularly for short period projects. The proposed approach demonstrated in the paper can sufficiently allow planning engineers to develop a comprehensive construction schedule so that the cost and time overruns in the lowest-bid awarded construction projects can be reduced. The paper provides empirical insights into how a robust construction schedule is developed from an owner's perspective. Cost-time optimization and risk analysis results obtained from manual computation might reduce the reasonable accuracy of the desired cost and schedule integration unless each activity is assigned its own calendar.

Keywords: *Cost optimization, CPM scheduling, critical path, project duration, resource allocation.*

INTRODUCTION

The construction industry has now turned out to be one of the major driving forces behind economic development of developing countries, such as Ethiopia. It contributes to high employment opportunity next to agriculture (EEA, 2008) and to income creation for the population, and it also contributes to government revenue through generation of corporate profit tax and income tax from employees. Thus, a small improvement in the construction sector will certainly generate lots of benefits. However, the level of construction project management practice during the design and construction stages is very low (Wubishet, 2004). As a result, the actual cost and duration of some projects substantially exceed that stipulated in the contract. Authors (Ayalew et al., 2016) reported that the public project underwent slippage up to 80 % and cost increased by 40 % from predetermined values. The cause of severe delay is due to ineffective planning (Gebrehiwet and Luo, 2017).

Most design engineers of public construction projects do not provide a comprehensive design report comprising realistic schedules and accurate measurements of quantities; as a result, cost overrun and time overrun have become a growing concern in the construction industry of developing countries. For example, earth work quantities (volume of rock or soil in trench excavation), construction period, and commencement date of most water supply construction projects executed over the past 10 years in Amhara region, Ethiopia, considerably deviate from the actual based on observation of 60 sample projects. It was reported that the public construction project delay was caused by limitations in the original schedule prepared during the pre-construction stage (Gebrehiwet and Luo, 2017). Furthermore, Bacon and Jones (1998) reported that 29 % underestimation was found in project duration of construction projects.

The standard construction and consultancy contract documents (MoWUD, 1995; PPA, 2010) do not pay attention to impacts of adverse weather against commencement date of a project. The threshold of adverse weather and corresponding number of delay-days are not also contained in most condition of contract documents, including FIDIC 1999. When a project period is set in calendar-days (CD), the schedule shall accurately estimate the commencement date and construction period in order to minimise impact of time-dependant constraints that might substantially reduce the applicability of the schedule. For example, period of some rural water supply construction projects is 7 months or 210-CD. The construction period of such a project may require 160 working days (WD) using maximum permissible resource and technology though its commencement date lies on the beginning of the rainy season (June in Ethiopia case). As a result, the actual available WD through June to December could be below 120 days due to adverse rainfall. Moreover, the right of way problem could set back the project by around 60-WD when pipe routes lie on the crops. Further, a large amount of local labour is required for pipe line excavation due to its inaccessibility for machineries. During harvesting season (October to January in the Ethiopian case), maintaining the anticipated performance during trench excavation is difficult due to unavailability of a sufficient number of local labour resources. Therefore, improper contract time or unfair risk transfer to contractor results in adversarial relationships, dispute, and contract termination.

Scheduling is highly dependent on optimization efforts and various types of uncertain variables; thus, it needs application of tools and techniques. The best approach to provide a robust schedule is a generate-and-test cycle for several alternatives until a satisfactory schedule is obtained. As a number of possible alternatives could be enormous, manual calculation of each alternative and iteration would be impossible. Several researchers have attempted to developed a schedule in a resource constrained environment using complex mathematical programming (Abeyasinghe et al., 2001; Cajzek and Klansek, 2016; Christodoulou et al., 2012; Franck et al., 2001; Heinz and Beck, 2011; Liu and Wang, 2008; and Ma et al., 2014), which is challenging to most construction planning engineers to apply it in their projects. It should also be noted that most of research has been conducted from a contractor's perspective; only the cost of construction (contractor) is considered. The authors have also used single precedence relation between activities which do not reflect the actual relation during execution of activities such as between trench excavation and pipe laying, pipe laying and backfilling, etc. These activities need both start-to-start (SS) and finish-to-finish (FF) precedence relations, otherwise a wrong result would be obtained when time-cost optimization is performed. Further, the impact of commencement-date and calendar on indirect cost of projects has comparatively been paid less attention during the planning stage when a project contract is set on a calendar day basis. Lack of appropriate risk assessment during the planning phase results in underestimation of project period, and such a problem triggers social and political pressure in public construction project areas.

The objective of the research is to provide a guiding document to help the planning engineers reasonably furnish a robust construction schedule (time program) for construction projects whose contract delivery is Bid-Build type. In order to address the complexity of mathematical program scheduling and to improve application of critical path method (CPM) scheduling, an integrated approach between mathematical programming and CPM scheduling in light of potential risks is demonstrated. Numerical example is provided, and nonlinear programming (NLP) and Oracle Primavera are used for time-cost optimization and CPM scheduling, respectively using realistic activity precedence constraints and different commencement dates. The cost-time optimization is performed from an owner's perspective; the cost comprises construction cost, supervision cost (consultant's or engineer's cost), and owner's overhead cost during project implementation. In order to draw a possible range between the worst and the best conditions of activity duration, 60 completed water supply construction projects are considered. Then, Monte Carlo simulation is performed on CPM schedule to foresee and accommodate the risk associated with delay. In addition, a schematic procedure is proposed by which planning engineers simply develop their schedule. Thus, the significance of the research relates to construction project scheduling during the planning phase.

1. CONSTRUCTION SCHEDULING

The performance of project is predominantly measured by cost, time, and quality; however, time (schedule) has direct impact on cost. Schedule slippage is one of the driving factors for cost overrun, claim, dispute, and contract termination in construction projects due to an increase in indirect costs.

Successful construction projects rely on a sound schedule that assimilates cost, time, and other technical data to help a project manager make efficient and effective decisions during construction execution. Nowadays the construction industry pursues a critical path method (deterministic time estimate) to create such a sound schedule. The common sequential procedures of CPM scheduling are developing work breakdown structure (WBS) and activity sequence, and allocating resource to activities so that the cost-time relation would be optimized. The dominant challenging task for scheduling is resource allocation in a constrained environment as it can drive cost, sequence, and duration of activities.

1.1. Resource Allocation and Levelling

When activities are conducted simultaneously, a peak resource demand is produced at a certain stage of construction project, and the peak may also happen several times. Firing skilled labour resources after the first peak and possessing them for next would be difficult, or holding them increases the cost of the project. Thus, scheduling of activities yielding a resource usage profile with frequent valley and peak indicates costly construction. Thus, it is desirable to allocate resources minimising their daily fluctuation as much as possible while the aggregate demand does not exceed the supply. Such resource allocation is known as resource levelling, and it is performed by shifting non-critical activities within their available float so as to minimise the idle time, thereby maximising the resource utilisation (DelPico, 2013). If the aggregate resource demand exceeds the resource supply after available float has once consumed, the project duration is forced to extend.

One of the scheduling approaches to fix the shortest construction period can be allocating of maximum amount of resources to critical path activities while effective management and follow up are maintained. The constraints would be resource supply, optimum operating space, and time (possible working hour or shifts, or project calendar in general). For non-critical path activities, resources can be allocated in a way to meet objectives: to minimise stockpiling of local material, to maximise the effectiveness and productivity of available plant and labour, to maintain optimal workflow to attain the best performance of resources, to maximise the effectiveness of management, and to optimise a net cash flow.

The number of supervisors would generally affect a minimum and maximum number of labour resources to maintain optimum interaction and thus productivity. Maintaining a supervisor-to-worker ratio between 1:8 to 1:20 is recommended (McTague and Jergeas, 2002). When the number of workers gets too large, some of them may not get the required attention and information they need from supervisors, and thus their productivity decreases. When there is no operating space constraint, an increasing number of workers reduce overburden among the workers, and then the project duration reduces. However, if the activity duration is much shorter than a typical duration by working overtime (weekend, evening) using a fewer number of workers or less equipment, the direct costs (*DC*) go up due to fatigue which decreases productivity and due to an additional fee for overtime. Overtime work is also prone to accidents and quality problems, which increase indirect costs. On the other hand, if the activity duration is much longer than typical duration having fewer workers than desirable, operating within normal working hours, the indirect cost (*IC*) of a project (contractor's indirect cost, consultant's supervision cost, owner's administration cost) would increase. Therefore, it is critically essential to schedule resources with an aim of optimising total cost (*TC*) and duration (*D*) of a project as shown in Fig. 1.

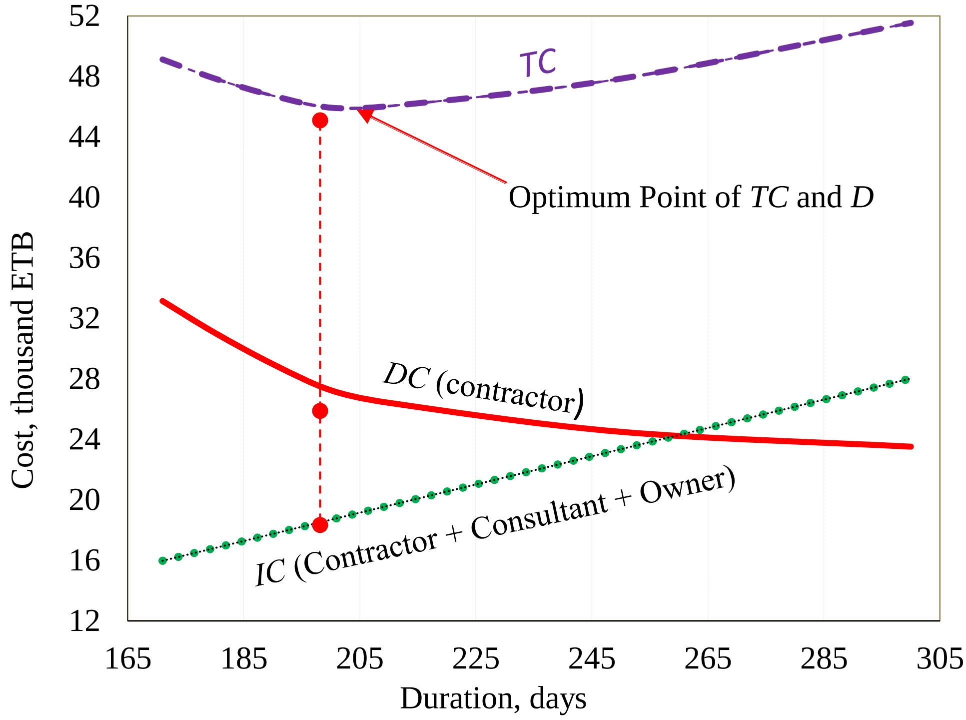

Fig. 1. Time-cost relationship in the construction project, cost in Ethiopian birr (ETB), duration in calendar days (developed by the author).

Risk analysis issues and information related to the construction contract award are described in the next subpart.

1.2. Risk Analysis

Although CPM is the most applicable scheduling approach, a critical path of a project may get altered and the project would delay during execution due to impact of adverse weather, variation in soil formation, and other unforeseen events within project activities. Thus, a range of duration of activities shall be simulated to improve a CPM schedule. The range of information allows showing a full spectrum of possibilities during project risk simulation in order to refine a time-cost estimate and to plan contingency in order to accommodate the risks. The most common technique that is used to simulate risks within the range of cost and schedule is Monte Carlo simulation (DelPico, 2013). It helps determine the likelihood of occurrence of activities to be critical path and the magnitude of their consequences.

1.3. Construction Contract Award

Awarding a construction project to an inappropriate contractor or the lowest bid price could take its part for a project failure attributed with cost overrun and time overrun for Design-Bid contract delivery system. It had been reported that awarding project to the lowest bid price is among severe causes of delay in the public construction project (Ibrahim et al., 2012). Such a problem has also become a growing concern in the Ethiopian public construction projects. Although the total estimated construction cost does not ultimately characterise the complexity and the effort required to a construction project, the current criterion for contractors to participate in water works tendering is to meet the grade-qualification indicated in Table 1. This grade-qualification specifies machinery and manpower to be possessed by a contractor, and the contractor will not be obliged to deploy machineries that required beyond his grade qualification. However, the planning engineers can better specify the contractor grade requirements based on resource requirements identified during a detailed time-cost analysis. For example, if there is a large volume of rock excavation for pipe trench and the activity lies on a critical path of the project requiring 10 excavators for each day to complete the project within contract time, whether the contractor grade qualification demands machinery or not, it is compulsory to deploy these excavators to complete the project. Another example, a labour-based project may cost 30 million for rural areas when average labour rate is 50 ETB/day, whereas it may cost 80 million ETB for urban areas when the rate is 150 ETB/day. Thus, adopting the total cost of a project as an ultimate criterion for contractor selection would bring cost and time overruns.

Table 1. Contractor Grade for Water Works Contractor (MoUD, 2013)

Grade	Project Cost (Maximum) in ETB	Starting Capital (ETB)
1	Above 200 Million	20 Million
2	200 Million	15 Million
3	100 Million	10 Million
4	50 Million	5 Million

Materials and methods are described in the next subpart.

2. MATERIALS AND METHODS

Water supply construction project comprising fourteen activities is used for a demonstration purpose, and its cost estimation and resource allocation are presented in Table 1 of Appendix 1. Earthwork and pipe work are supposed to be executed by labour due to inaccessibility of pipe routes to machineries. In addition, the maximum supply of daily-labour (DL) is assumed 340 number/day, whereas availability of other resources is assumed to be unlimited.

For cost estimation purposes, 70 % of the total construction cost is taken as direct cost and 30 % – as indirect cost. In addition, 5 % and 0.5 % of the total construction costs are considered to be consultant's supervision and owner's administration costs, respectively. Polynomial 2nd degree function is employed for direct cost-time function for nonlinear programming (NLP). Excel solver and LINGO 17 optimization software is employed to find an optimum cost-schedule scenario. For financial comparison of normal-time to crash-time, 1 % monthly interest is considered during PMT (periodic payment) and NPV (net present worth) calculation.

Based on the project record of 60 completed water supply construction projects, the major delay factors noted are variation in soil formation, delay in supply of electromechanical equipment, unforeseen adverse rainfall, and variation in productivity of crew, and these are considered for risk analysis. It has been noticed that 85 % of the project electromechanical installation underwent slippage from two to six months due to delay in procurement process of pump and generator. Thus, the author assumes that Activity-M, supply and installation of pump and generator, may delay by 2 months (40-WD) as such materials are often imported from abroad, particularly for developing countries. For the rest of activity, a modified standard risk banding, 0.9 for optimistic and 1.3 for pessimistic multiplier of deterministic duration, is used to produce three-point duration. Such an initial qualitative risk analysis or three-point duration is presented in Table 4 (Appendix 1), and the optimistic duration is considered to be determinist duration for CPM scheduling. Furthermore, it has been noted that out of 60 sample projects 35 projects showed that their actual commencement date had slipped by 4 months and above from the date determined during the planning phase. Thus, four group commencement periods have been identified based on construction time overlap with rainy season, and the CPM schedule and cost-time optimization have been tested for the worst and best commencement dates.

Then a quantitative analysis is performed using Monte Carlo simulation in both manual method (Microsoft excel) and software (Primavera P6 Risk Analysis). For the manual method, the probabilistic duration (D_n) is computed in Excel function as follows:

$$D_n = \text{Beta.Inv}\left(P_n, \alpha, \beta, D_\text{p}, D_\text{o}\right), \tag{1}$$

where

Beta. Inv	is the inverse of the beta cumulative probability density function,
P_n	is probability of duration (d) of n^{th} sample associated with the beta distribution,
α (alpha)	is the parameter of distribution (shape factor),
β (beta)	is the parameter of distribution (skewness factor),
D_p	is the pessimistic duration (lower bound),
D_o	is the optimistic duration (upper bound).

The sample size (n) for Monte Carlo simulation is determined on the basis that simulated mean falls within 99 % confidence level, and error of the mean does not exceed 1 %. In addition, positively skewed beta distribution function ($\beta > \alpha$) is employed as the probability of public project early completion is less likely than late completion. From the risk analysis result, distribution of project durations with their probability of occurrences, final CPM schedule is selected with contingency plans.

3. DISCUSSION AND ANALYSIS

The major procedures for schedule creation during detail engineering design can be modelled by the framework shown in Fig. 3, and its major steps are discussed below.

Stage 1 (CPM Scheduling): First, activities that define the scope of a project are determined. Second, the calendar of each activity or the calendar of the project is defined and allocated to each activity in order to account holydays, weekends, overtime, and foreseen non-working days. Third, logical sequencing of activities is set out. Fourth, the duration activity is determined as shown in Equation 2 and will be iterated until optimum criteria of resource allocation are satisfied.

$$D_i = \frac{Q_i}{N_{ij} \cdot P_{\mathrm{u}j}}, \tag{2}$$

where

- D_i is the duration for activity i,
- Q_i is the quantity of activity i,
- N_{ij} is a number of unit crew j for activity i,
- $P_{\mathrm{u}j}$ is productivity of unit crew j.

The first step of resource allocation starts by selecting a unit crew containing machinery or labour based on availability, productivity, accessibility, and methodology. The final resource (N_{ij}) that would give the shortest practical duration is iterated while workflow and precedence constraints are satisfied. For example, for efficient workflow, Activity C and D are set to have equal durations as seen in Fig. 2(a) and Fig. 5. Trench cannot be left open beyond length specified in technical specification.

The other constraint considered is operating space. For example, a unit-crew consisting of 1-gang leader (GL) and 10-daily labour (DL) may excavate around 40-metre-long trench section each day (1-DL / 4 m length of working space); as a result, 750 unit-crew (30 km / 40 m) can be allocated for Activity C in order to get it completed within a day for 8 working hours per day. However, such allocation is not desirable due to the following major constraints: labour supply limit (340 DL per day), wastage and productivity loss, rate of execution of preceding and succeeding activities, accessibility and permit of all sections within a day, and anticipated financial and management risks. Another example, if 120 m² HCB work is available (3-meter high and 40 m perimeter), only 4 mason-crew can be allocated to have the installation completed within a day because a unit mason-crew can install around 10 m² hollow block (HCB) daily (8-hr), so that 10-m long continuous span working space is required daily as the height of the blocks to be placed may not technically exceed 1-meter (five block vertically) when a mortar made from ordinary Portland cement is used as binding between blocks.

Reasonable allocation is made for this sample project based on above principles (see Table 1 of Appendix 1), and then the total project period is computed by adding activity durations along the network (Fig. 4) or can be automatically generated using scheduling software (Fig. 5), and then the aggregate resource demand is checked against supply limit as seen in Figs. 5–6. If the demand is greater than the anticipated supply limit, adjustment is required to reduce allocation either by resource levelling operation under scheduling software, or manual reducing of N_{ij} starting from non-critical to critical activities until the desired result is obtained while an increase in the associated cost for overtime work is considered.

More robust modification can manually be made to scheduling software because resource levelling could extend a project period than the resource deficit. For example, if DL supply limit is 250, the project period could be extended by 55-WD due to DL deficit when concrete is poured in Activity H and/or Activity K planned at the same day with Activity C-D-E. However, if Activity C & Activity E are paused or some of their workers are shifted into Activity H and/or Activity K during peak demand, a shorter and practical schedule can be obtained. As the supply limit is satisfied in this project case, the next step is to find an optimal cost-schedule scenario.

The final results of this stage are: activity sequence (Fig. 4 and Table 2 of Appendix 1); anticipated day-lost due to adverse rainfall (Table 3 of Appendix 1); activist's duration (D_i) and corresponding crew (N_{ij}) (Table 1 of Appendix 1); and total project period 140-WD (204-CD for 5-working days/week or 40-hr/week for September-1/2017, i.e., the construction start date) (Fig. 5).

Stage 2 (Cost-time Optimization): At this stage, normal DC of the project is computed based on allocated resources (labour, machine/equipment, material, time or duration) during stage 1. The construction unit-cost indicated in Table 1 of Appendix 1 is drawn from cost breakdown of labour, equipment and/or machine, and materials with normal working hours. Therefore, the construction project is supposed to consume the 140-WD, herein referred to as normal time with normal construction cost.

The crashed-DC presented in Table 2 of Appendix 1 comprises normal DC plus overtime cost, additional cost to compensate productivity loss due to overburden and risk costs for time crashing scenario. Maximum time crashing is done until available and permissible overtime is consumed. For instance, if 5-WD/week and 8-hr/day are an accepted calendar, a crashed alternative can be a calendar with 7-WD/week for 8-hr/day, or 7-WD/week for 10-hr/day. Based on such an approach the resulting crashed cost-time function can be represented as seen in Table 2 of Appendix 1.

The indirect cost (IC) of an activity can be computed multiplying its daily cost by duration (calendar duration). Then TC is iterated until the lowest value is obtained between crash and normal times, and the objective function can be represented as follows:

$$\text{Minimize } TC = \sum_{i=1}^{14} D_i \cdot DC_i + k \cdot D \cdot IC. \quad (3)$$

Subject to the constraints:

$$S_i + D_i + L_{ij} \leq S_j; \quad (4)$$

$$S_i + L_{ij} \leq S_j; \quad (5)$$

$$S_i + D_i + L_{ij} \leq D_i + S_j; \quad (6)$$

$$D_{\text{cr}} \leq D_i \leq D_{\text{nr}}; \quad (7)$$

$$D = \sum_{i=1}^{3} D_i + \max\{\sum_{i=4}^{4} D_i + \sum_{i=4}^{5} L_{ij}, \sum_{i=7}^{10} D_i + D_{14}, \sum_{i=11}^{13} D_i\}, \tag{8}$$

where S_i is the start time of activity i, S_j is the start time of activity j, D_i is the activity duration, L_{ij} is the lag/lead time between activity i and the succeeding activity j, D_{cr} is the minimum time (maximum crashed-time) of activity i, D_{nr} is the normal duration of activity i, D is the maximum total duration (in working days) of the project out of possible paths in Fig. 5, k is the conversion factor of WD into CD based on a project calendar. Equations 4–6 represent the precedence relation between activities.

The summarised results of NLP of cost-time optimization are presented in Table 2, and detailed information can be seen in Table 2 of Appendix 1. When double precedence is imposed between Activity C and D (see Fig. 2a), *TC* of the project is around 42.8 million yielding 125-WD (153-CD) for September commencement date as seen in Table 2, whereas the lower value of *TC* (40.066 million and 116-WD) is obtained when single precedence is imposed. However, non-realistic result would be obtained; pipe laying is planned to start ahead of trench excavation as seen in Fig. 2b when FF precedence relation is used. If SS precedence relation is used, trench excavation would complete 20-WD earlier than pipe laying, which is technically unacceptable. For June commencement date, the crashing scenario yields *TC* 43.51 million and corresponding time 120-WD (178-CD) is obtained. Thus, if the planned start dates (September–November) of project may slip to the worst scenario (February–June), the total cost would increase by around 2.88 and 2.29 million for normal and crashing scenarios, respectively (Table 2).

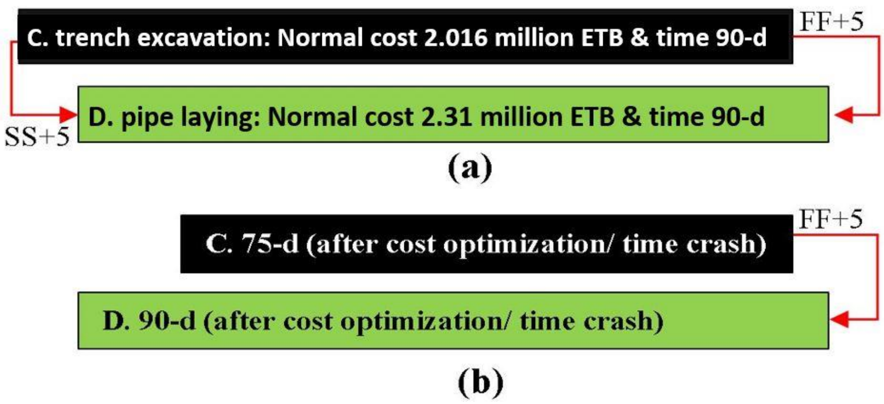

Fig. 2. Relation between activities; (a) double precedence, (b) single precedence after cost-time optimization (developed by the author).

Upon financial comparison of crashed and normal time scenarios, the crashed alternative gives lower *TC*. Finally, after cost-time optimal relation is obtained here, possible risk associated with cost and time shall be assessed.

Stage 3 (Risk Analysis): At this stage, the impact of adverse weather or delay in construction start date on project period (CPM Schedule) and on total cost is analysed. Based on schedule developed at stage 1 (see Figs. 5–6), the period of project time overlap with rainy season (June–August) is identified, and then the optimist (S_o) and pessimistic (S_p) scenarios are classified. February to June levelled as the highest risk dates (S_p) because of 3-calendar-month overlap. September to November commencement dates would not overlap with rainfall season (S_o).

Based on a simple statistical analysis, the likely occurrence of "S_o" commencement date is 25 % (3/12, month ratio). If the project were planned to commence in this period and actually started between February and June, the impact would be an increase in *IC* by around 2.95 million and 20 % time overrun as seen in Table 1 of Appendix 1 and Figs. 5–6 unless calendar modification was done for "S_p". The cost increase does not include loss of revenue of the project owner due to delay. However, if the project has already commenced within Sep-Nov and if the delay occurs due to right of way issue due to owner (for example, crop cover in pipe route), the resulted increase in cost would be: owner's overhead and loss of revenue due to delay and consultant's/engineer's cost.

For a quantitative analysis, the expected project duration is iterated 8,000 times using Monte Carlo simulation, and its likelihood of occurrence is presented in Figs. 7–8. It has been noticed that the critical path identified using CPM, activity "A-B-C-D-E-N", has around 85 % likelihood of occurrence, and activity "A-B-F-G-H-I-M-N" can have around 15 % likelihood of occurrence to be a critical path. The planning engineer is aware of that if previous construction trend continues, the contract periods determined using CPM scheduling at stage 1 have less than 40 % likeliness of occurrence (greater than 60 % risk) and the project can be completed within 165-WD with 10 % risk (90 % confidence level). In general, 10 % risk is acceptable in construction, and the owner's reserve contingency for this risk provides that the original cost-time meets 90 % confidence level.

The total cost reduction due to crashing is 3.1 & 3.8 million ETB for "So" and "Sp", respectively as seen in Table 2. Time crash scheduling scenario increases the project risk as an additional activity path becomes critical. However, it may save a substantial amount of cost for both owner and contractor provided that the crashing alternative is practical.

Based on the risk analysis result, mitigation measure can be introduced in the condition of contracts of construction execution. For instance, the risk of project delay because of Activity M can be reduced by introducing contractual terms: "purchase order for pump and generator shall be issued immediately after the contractor receives advance payment". Furthermore, when there are different applicable methodologies for a certain activity (for example, machine-based and/or labour-based crews), the range of cost-time analysis and tender evaluation shall be done accordingly. This is particularly very important in developing countries for the lowest-bid awarded projects because several projects undergo cost and time overruns due to improper planning and bid evaluation. Such problems can be averted if planning engineers furnish project owner's realistic schedule with a range of costs in different possible scenarios, and the bid evaluation complies with a range of cost-time identified during planning.

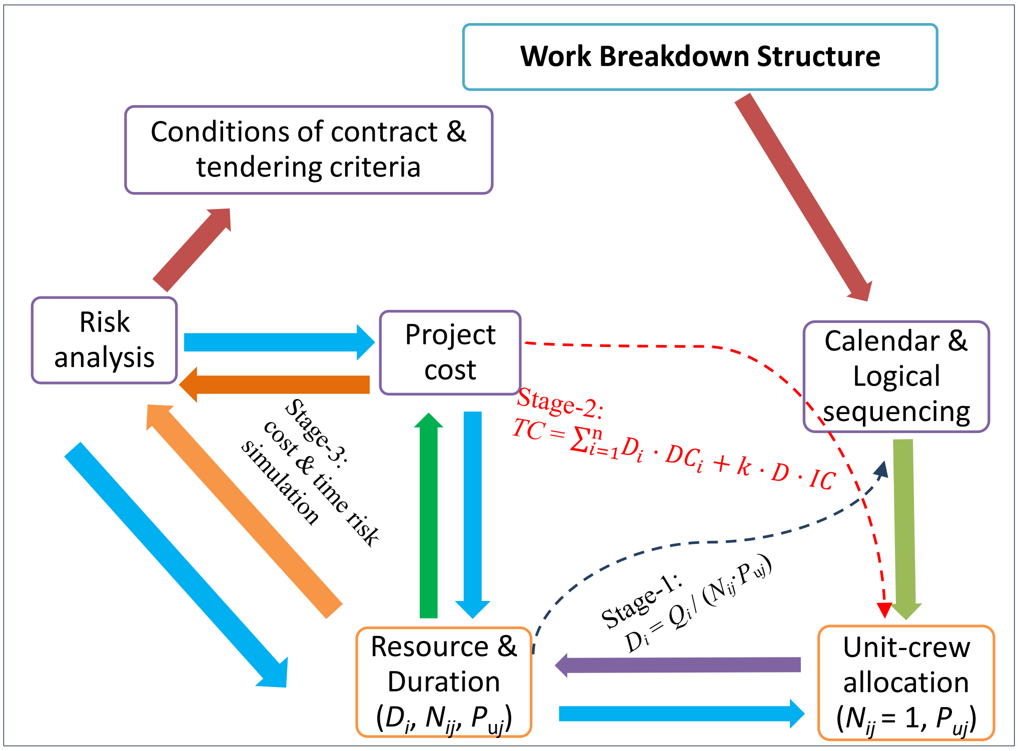

Fig. 3. Framework for construction project scheduling at the planning phase (developed by the author).

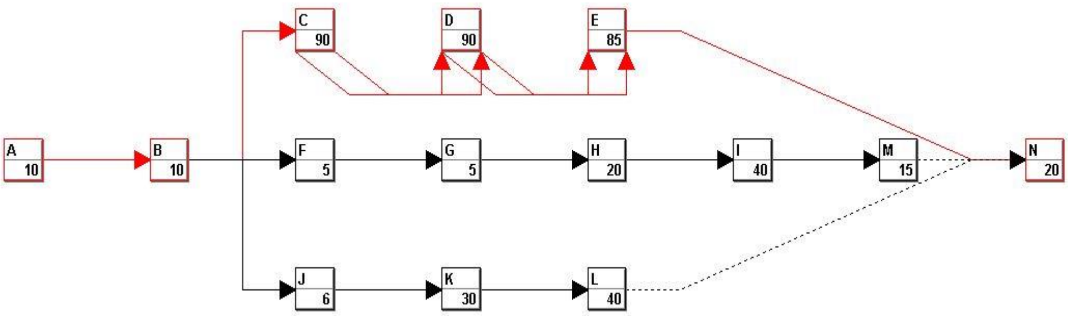

Fig. 4. Activity network diagram (critical path: A-B-C-D-E-N) (developed by the author).

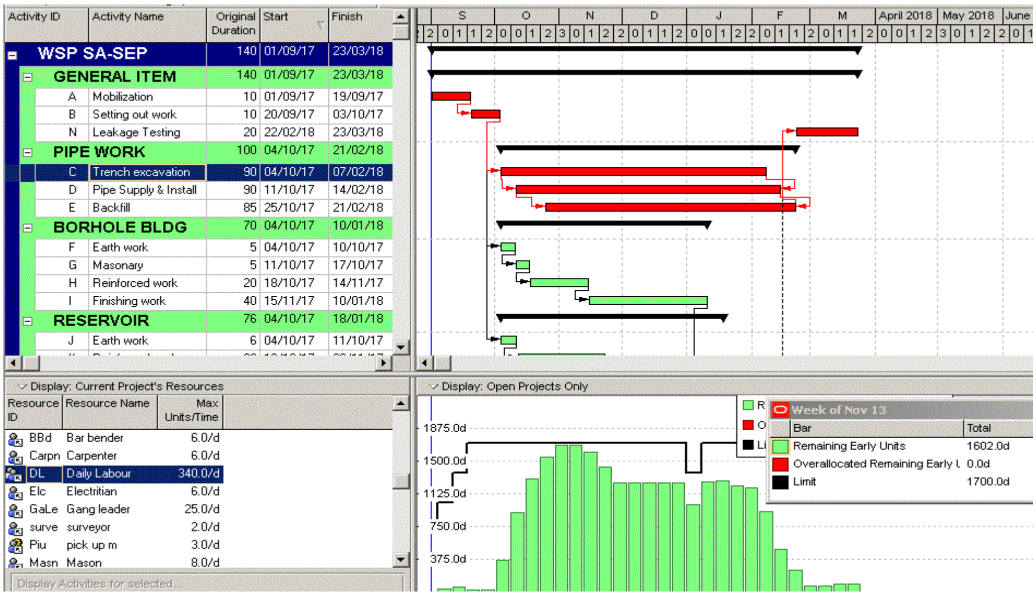

Fig. 5. Weekly DL usage (normal time) for September commencement date (developed by the author).

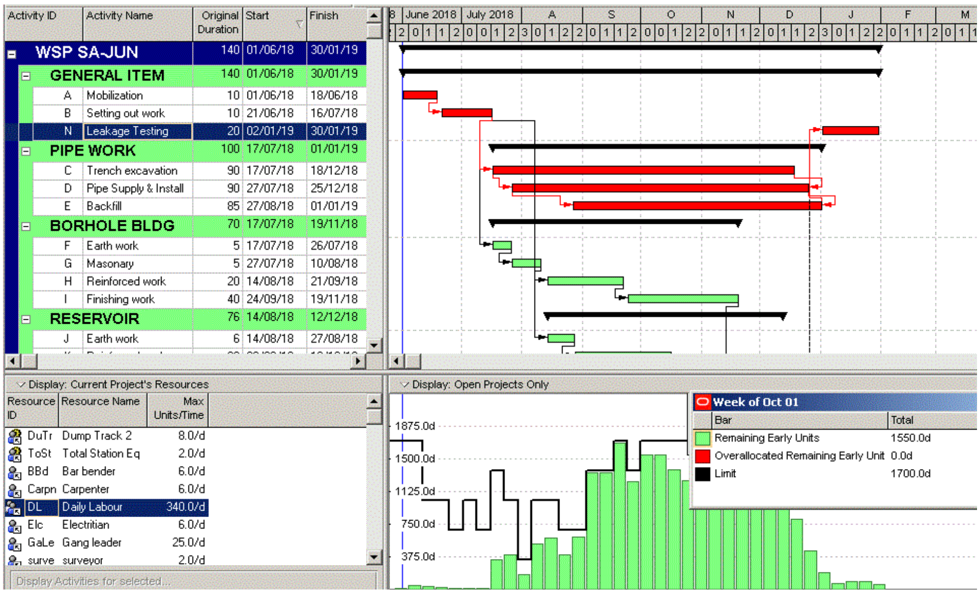

Fig. 6. Weekly DL usage (normal time) for June commencement date (developed by the author).

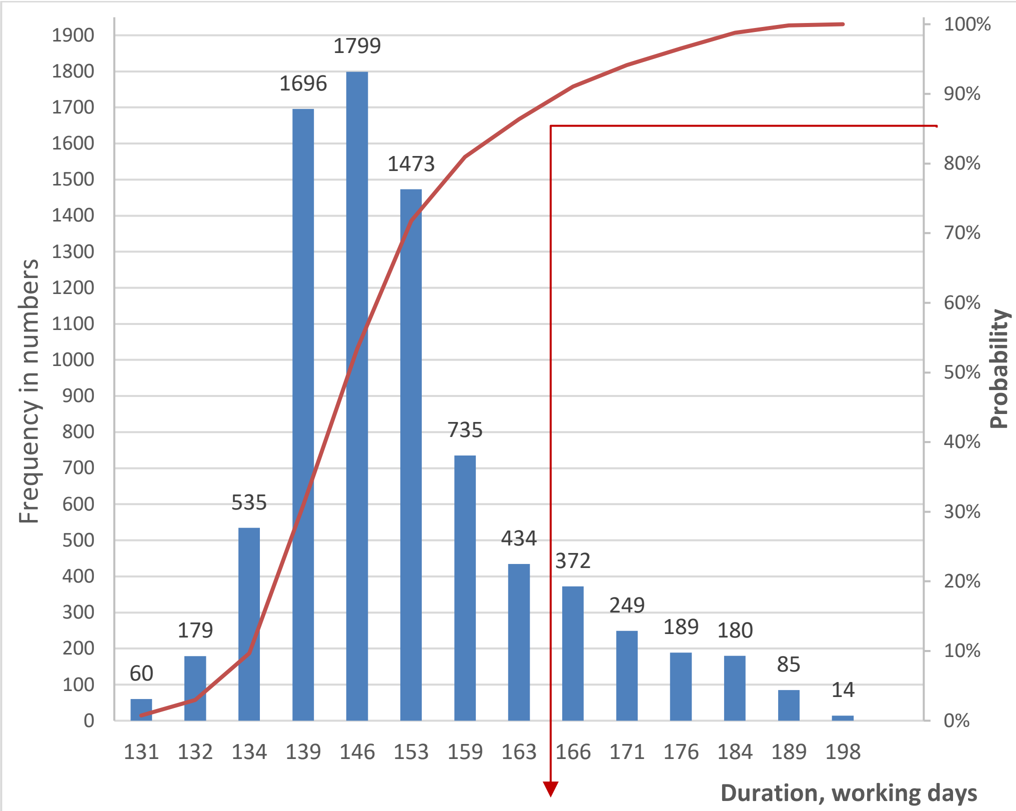

Fig. 7. Results of manual Monte Carlo simulation
(beta distribution: α = 2, β = 4, mean = 149) (developed by the author).

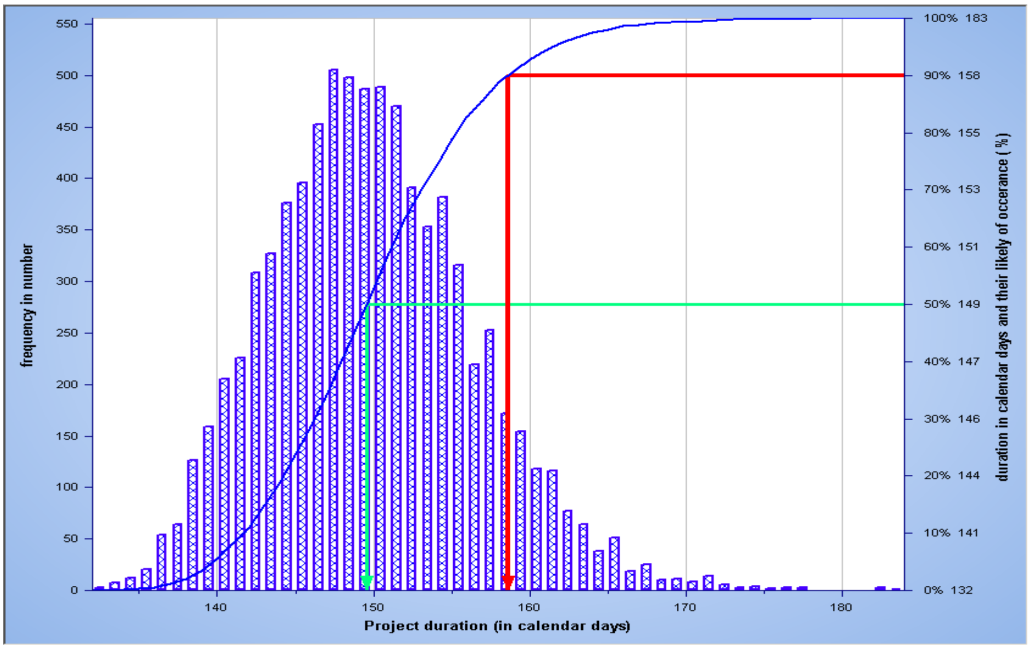

Fig. 8. Results of Monte Carlo simulation using Primavera Risk analysis software
(7-day calendar used, mean = 149) (developed by the author).

Table 2. Optimal Value of Cost and Schedule for the Worst and Best Project Start Date (developed by the author)

	S_o (Sept–Nov)		S_p (Feb–June)	
Schedule type	Normal	Crashed	Normal	Crashed
Duration (WD)	140	125	140	120
k	1.46 (204/140)	1.22	1.74 (244/140)	1.48
DC (million ETB)	29.755	30.217	29.755	30.751
IC total (million ETB)	14.657	10.999	17.504	12.758
TC (million ETB)	44.412	41.216	47.259	43.509
Cost consultant (million ETB)	2.065	1.55	2.466	1.797
Start date probability	25 %	–	42 % (5/12)	–

Conclusions are summarised further.

CONCLUSION

The proposed approach integrates resource constraints, scheduling software, mathematical programming, and commencement date issues, while cost and time are optimised from the project's owner perspective. Cost-time optimization could yield a non-realistic result unless double precedence relations (SS plus FF) are applied between activities, such as trench excavation and pipe laying, pipe laying and backfilling, etc. It has been noticed that the start date of the project substantially affects the schedule and the total cost of the project, thus planning engineers need to pay attention to this issue. As mathematical programming for time-cost optimization performs time crashing based on well-known criteria, a practitioner can obtain near optimal cost-time without such a complex approach. Particularly scheduling software can ease scheduling for a practitioner subjected to some manual adjustments to cost-time relation.

When cost and schedule are used as criteria for tender award, the applicability of cost and schedule submitted by the bidders shall be thoroughly checked against detail schedule prepared during the planning phase. This allows the project owner to choose a bid with applicable construction methodology and duration that would give the lowest total cost. Accordingly, a project failure as a result of the lowest-bid award and associated poor project execution can be averted if a planner furnishes project owner's or consultant's detail schedule at the planning phase. The study intended to provide a simple and practical approach for construction planners, and thus could be a basis for further research in the field of construction planning and scheduling.

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AUTHOR'S SHORT BIOGRAPHY

Matiwos Tsegaye received his *B. sc.* in Civil Engineering in July 2007, and *M. sc.* in Civil Engineering (construction technology and management) in February 2017 at the Institute of Technology of Bahir Dar University, Ethiopia.
He has worked for 11 years in different positions related to civil engineering construction projects at local and international construction companies. Currently, he works as a Project Manager of Water Works Construction Consultant in Bahir Dar, Ethiopia.
Phone: +251935982606
E-mail: matiwostse@gmail.com
ORCID iD: https://orcid.org/0000-0002-2897-8292

APPENDIX 1

Table 1. Resource Allocation and Construction Cost Estimation Sheet (developed by the author)

Activity Name	Unit	QTY	Unit crew output per unit	No unit crew	Labour	Duration	Rate (thousand ETB)	Amount (thousand ETB)
Mobilization	Ls	1	10	1	1Foreman:10 DL	10	200	200
Setting out work	km	30	3	1	2Surveyor:5DL	10	2	60.000
Leakage testing	km	30	0.33	3	3Plumber: 6DL	20	4.5	135
Trench excavation	m^3	14 400	15	11	1Gang leader: 10 DL	90	0.2	2.880
Pipe supply & install	km	30	112	3	1Plumber:16DL	90	1.1	33.000
Backfill	m^3	14 400	25	7	1Gang leader: 10 DL	85	0.06	864
Earth work	m^3	25	5	1	0.5 Gang leader: 5 DL	5	0.06	1.5
Masonry	m^3	30	1.5	4	1Mason:4DL	5	2	60
Reinforced work	m^3	16	0.2	2	1Carpenter: 1mason: 1barbender: 18DL	20	5	80
Finishing work	Ls	1	0.013	2	1carptenter: 1mason: 10 DL	40	900	900
Earth work	m^3	60	5	2	0.5 Gang leader: 5 DL	6	0.11	6.6
Reinforced work	m^3	24	0.2	4	1Carpenter: 1mason: 1barbender: 18DL	30	5	120
Finishing work	Ls	1	0.013	2	1carptenter: 1mason: 10 DL	40	700	700

Activity Name	Unit	QTY	Unit crew output per unit	No unit crew	Labour	Duration	Rate (thousand ETB)	Amount (thousand ETB)
EM supply & install	Ls	1	15d	3	1Electrician: 1Plumber:8 DL	15	3.500	3.500
Total construction cost including profit and overhead								42 507.1

Table 2. Cost-time Optimization Result Obtained Using Excel Solver for the Best Commencement Date Scenario (developed by the author)

Activity No	Predecessors	Relation	Lag (day)	D_i (day)			DC (thousand ETB)			Direct cost (DC) – Duration (D_i) function
				Normal	Crash		Normal	Crash		
1		–	–	10	–	–	140	–	–	140
2	A	FS	0	10	7	7	42	52	52	$1.44 \cdot D_2^2 - 22.87 \cdot D_2 + 176.37$
3	E, L, M	–	0	20	14	14	94.5	116	116	$1.083 \cdot D_3^2 - 40.4 \cdot D_3 + 469.38$
4	B	FS	0	90	84	75	2016	2051.5	2122	$0.069 \cdot D_4^2 - 18.51 \cdot D_4 + 3120$
5	C	SS&FF	5&5	90	84	75	23 100	23 490.8	24 362	$1.43 \cdot D_5^2 - 319.53 \cdot D_5 + 40\,302$
6	D	SS&FF	10&5	85	79	70	604.8	611.61	652	$0.2 \cdot D_6^2 - 34.52 \cdot D_6 + 2076.64$
7	B	FS	0	5	5	3	1.05	1.05	1.42	$0.59 \cdot D_7^2 - 0.66 \cdot D_7 + 2.86$

Activity No	Predecessors	Relation	Lag (day)	D_i (day)			DC (thousand ETB)			Direct cost (DC) – Duration (D_i) function
				Normal	Crash		Normal	Crash		
8	F	FS	0	5	5	3	42	42.00	62	$4.96 \cdot D_8^2 - 49.68 \cdot D_8 + 166.4$
9	G	FS	0	20	18	14	56	53.83	72	$0.91 \cdot D_9^2 - 33.72 \cdot D_9 + 365.1$
10	H	FS	0	40	40	27	630	630	708	$0.43 \cdot D_{10}^2 - 34.48 \cdot D_{10} + 1329$
11	B	FS	0	6	6	4	4.62	4.6	6.60	$0.3 \cdot D_{11}^2 - 0.4 \cdot D_{11} + 17.7$
12	J	FS	0	30	30	27	84	84.0	103	$0.5 \cdot D_{12}^2 - 30 \cdot D_{12} + 535.8$
13	K	FS	0	40	40	27	490	490	546	$0.26 \cdot D_{13}^2 - 22.03 \cdot D_{13} + 951.6$
14	I	FS	0	15	–	–	2450	–	–	2.450

Table 3. Anticipated Monthly Working-Day Lost Due to Adverse Rainfall (developed by the author)

Month	Working days lost	Month	Working days lost
January	–	July	11
February	–	August	12
March	–	September	–
April	–	October	–
May	–	November	–
June	9	December	–

Table 4. Time Estimate for Risk Analysis (developed by the author)

Activity ID	Optimistic (a)	Most likely (m)	Pessimistic (b)
A	9	10	13
B	9	10	13
C	81	90	117
D	81	90	117
E	76	85	112
F	4	5	7
G	4	5	7
H	18	20	26
I	36	40	52
J	4	6	8
K	27	30	39
L	36	40	52
M	13	15	55
N	18	20	26