Time-Cost-Quality Trade-off in Construction Project Management

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Abstract
The three interrelated and conflicting objectives of any project are time, cost, and quality. In today's competitive business environment, delivering projects in the least possible time, with maximum quality and minimum cost has got a critical issue for project managers. Project time crashing plays an important role in project management determining which activities duration to crash to complete the project in the stipulated time. In this paper, it is suggested that the project quality may be affected by project crashing and an actual construction project has been considered to study the tradeoffs among time, cost, and quality. The purpose is to highlight the managerial insights gained, as well as pointing out key problems and difficulties faced. The project is scheduled in Microsoft Project and crashed using the Solver add-in of Microsoft Excel. Using this construction example, quality level curves are generated to illustrate the trade-offs among time, cost, and quality. These level curves can then be used by project managers to make project scheduling decisions that explicitly model and consider quality as well as time and cost, so that better and more appropriate decisions can be made for a particular situation.

Keywords— *Time-cost-quality trade-off, project crashing.*

I. INTRODUCTION

In the management of a project, it is often possible to compress/crash the duration of some of the activities at an additional expense in order to reduce the total project's duration, and generally there is a due date for project completion. So a decision problem considered in the project management literature is to determine the activities for crashing and also the extent of crashing. By assuming that the direct cost (hereafter called cost) of an activity varies with time (limited by normal and crash times), linear programming models were developed to minimize the project direct cost. The problem is known as time/cost trade-off problem in the project management literature. This paper reports on the second phase of a study conducted by the author on Trade-off Analysis in construction projects. The first phase produced a paper on "*Project crashing to solve Time-Cost Trade-off*", which was described in the 2016 issue of the *SSRG International Journal of Civil Engineering (SSRG-IJCE)*. The following paper adds Quality as another important constraint to extend the problem statement to solve the Time-Cost-Quality Trade-off for an actual construction project**.** Babu and Suresh (1996) were the first who suggested that the quality of a completed project may be affected by project crashing. They assumed that quality of a project is a function of the quality of its activities, and also assumed that cost and quality of each activity varies linearly with activity completion time. For simplicity, they adopted the continuous scale from Zero to One to specify quality attained by each activity. The overall project quality is a function of quality levels attained by the individual activities. In Khang and Myint (1999), model proposed by Babu and Suresh (1996) was applied to an actual cement factory construction project. Time cost quality trade-off has been thereafter researched from a mathematical point of view using heavy mathematical programming methods and softwares. This paper focuses more on the decision making aspect of the trade-off analysis and uses an easily available, user friendly Microsoft Excel Solver Add-in for analysis. This research also validates with real data most of the findings by Khang and Myint in their original work.

Construction of a real time structure involves thousands of activities including not only civil but also mechanical, electrical & various other aspects. The project considered for this paper is that of a Residential Building in Kolte Patil I Ven Township "Life Republic" Jhambe Marunji Hinjewadi Pune. For academic purposes, the scope of this paper limits to the planning & crashing of only RCC works of the tower A of Residential sector R3. The project is scheduled in Microsoft Project and since manual crashing of the project of this scale will prove tedious and unnecessarily time consuming, the paper uses an add-in of Microsoft Excel called Excel Solver.

The first section of this paper presents the problem statement formulated comprising of the complexities involved in crashing of the construction project.

The second section presents the analysis of the crashing problem with a view to determine an optimum completion time of the project at minimum cost and maximum quality.

In the third section, Time-Cost-Quality trade-off discussions concerning the project are then carried out based on the output of the analysis and conclusions are drawn.

II. PROBLEM STATEMENT & METHODOLOGY OF WORK

A. Problem Definition:

A project is represented by its activities i, each of which is associated with its time T_i, cost C_i and quality Qi.

To manually calculate the earliest/latest times (ES/EF/LS/LF) for each activity *i* can be quite time consuming and tedious using the forward-backward passes. Thus for this paper, these times are calculated in Microsoft Excel using specific formulae, explained in Section II.

To encapsulate, Project Time-Cost-Quality Trade-off Problem can be formally stated as follows: given a network with a lot of activities by their sequences, durations, costs and qualities, a general status is determined by each activity according to at least one of the following objectives: minimize the project duration, maximize the construction quality and minimize budget.

B. Problem Statement:

Kolte-Patil Developers Ltd is a leading Pune-based real estate company. The company has developed and constructed 42 projects including 30 residential complexes, 8 commercial complexes, and 4 information technology parks across Pune and Bangalore. The Township of Life Republic is an ongoing project by Kolte Patil Developers which commenced in 2010. The total cost of the whole project is estimated to be 11,000 crores.

The scope of work for the whole project is large and complex since the vast 400 acre of township area is planned to be developed into several sectors containing Infrastructural Projects, Residential Projects, Commercial, Retail, Entertainment & Recreational, Educational, Sports, Health Sectors, Urban Farm, Management & Maintenance Projects. A residential tower "A" in the residential sector "R3" of the township has been chosen for the analysis of Time-Cost-Quality Tradeoff.

Considering the fact that the construction of this residential tower is subject to a large number of exogenous factors, mostly economical & beyond the scope of the top management, it was decided to focus this research on only the RCC works of the residential tower A in sector R3. Table I summarizes the data related to the RCC works of the tower A.

The challenge is of bringing the project on schedule and even finishing early, without compromising on its quality.

Adding up these times gives a grand total of 1631 days, which is far too much time for the construction of a residential building. Fortunately, some of the activities can be done in parallel, which substantially reduces the project completion time. Given all the information in Table I, answers have to be developed to the following questions.

1. What is the total time, cost & quality required to complete the project if no delays occur?
2. When can the project be completed at the earliest and at what cost and quality?
3. If extra money is spent to expedite the project, what is the least expensive way of attempting to crash the project duration while maintaining a tolerable quality level of 95%?

TABLE I : PROJECT DATA

ID	Activity Name	Normal Duration	Normal Cost
1	**RCC**		
2	**Substructure:**		
3	***Footings***		
4	PCC below footings	55 days	4,60,156
5	Reinforcement Fixing	56 days	8,20,954
6	Shuttering	52 days	2,63,487
7	Concreting	49 days	7,95,369
8	Deshuttering	49 days	2,63,487
9	***Column & lift pardi upto Plinth beam***		
10	**1st Step**		
11	Reinforcement Fixing	42 days	8,20,954
12	Shuttering	45 days	2,63,487
13	Concreting	43 days	7,95,369
14	Deshuttering	43 days	2,63,487
15	**2nd Step**		
16	Reinforcement Fixing	35 days	8,20,954
17	Shuttering	35 days	2,63,487
18	Concreting	35 days	7,95,369
19	Deshuttering	35 days	2,63,487
20	**Plinth Beams**		
21	PCC below Plinth beams	12 days	89,284
22	Reinforcement Fixing	17 days	8,20,954
23	Shuttering	16 days	2,63,487
24	Concreting	16 days	7,95,369
25	Deshuttering	17 days	2,63,487
ID	**Activity Name**	**Normal Duration**	**Normal Cost**
26	PCC for plinth	25 days	4,05,212
27	***Construction of Parking Floor Slab (Conventional Shuttering)***		
28	**West side half portion**		
29	Column / Retaining wall	24 days	21,43,292
30	Reinforcement Fixing	20 days	8,20,954
31	Shuttering	20 days	5,26,969
32	Concreting	20 days	7,95,369

33	Slab	44 days	21,43,292
34	Shuttering	42 days	5,26,969
35	Reinforcement placing	40 days	8,20,954
36	Concreting	1 day	7,95,369
37	**East side half portion**		
38	**Column / Retaining wall**		
39	Reinforcement Fixing	45 days	8,20,954
40	Shuttering	45 days	5,26,969
41	Concreting	48 days	7,95,369
42	**Slab**		
43	Shuttering	29 days	5,26,969
44	Reinforcement placing	27 days	8,20,954
45	Concreting	1 day	7,95,369
46	**Superstructure**		
47	***Aluform RCC Slab Cycle***		
48	**1st Floor**		
49	Part 1	30 days	287,90,559
50	Part 2	25 days	287,90,559
51	**2nd Floor**		
52	Part 1	20 days	287,90,559
53	Part 2	20 days	287,90,559
54	**3rd Floor**		
55	Part 1	15 days	287,90,559
56	Part 2	15 days	287,90,559
57	**4th Floor**		
58	Part 1	10 days	287,90,559
59	Part 2	10 days	287,90,559
60	**5th Floor**		
61	Part 1	10 days	287,90,559
ID	**Activity Name**	**Normal Duration**	**Normal Cost**
62	Part 2	10 days	287,90,559
63	**6th Floor**		
64	Part 1	10 days	287,90,559
65	Part 2	10 days	287,90,559
66	**7th Floor**		
67	Part 1	10 days	287,90,559
68	Part 2	10 days	287,90,559
69	**8th Floor**		
70	Part 1	10 days	287,90,559
71	Part 2	10 days	287,90,559
72	**9th Floor**		
73	Part 1	10 days	287,90,559
74	Part 2	10 days	287,90,559
75	**10th Floor**		
76	Part 1	10 days	287,90,559
77	Part 2	10 days	287,90,559
78	**11th Floor**		
79	Part 1	10 days	287,90,559
80	Part 2	10 days	287,90,559
81	**12th Floor**		
82	Part 1	10 days	287,98,952
83	Part 2	10 days	287,98,952
84	**13th Floor**		
85	Part 1	10 days	287,98,952
86	Part 2	10 days	287,98,952
87	**14th Floor**		
88	Part 1	10 days	287,98,952
89	Part 2	10 days	287,98,952
90	**15th Floor**		
91	Part 1	10 days	287,98,952
92	Part 2	10 days	287,98,952
93	**16th Floor**		
94	Part 1	10 days	287,98,952
95	Part 2	10 days	287,98,952
96	**17th Floor**		
97	Part 1	10 days	287,98,952
98	Part 2	10 days	287,98,952
99	**18th Floor**		
100	Part 1	10 days	287,98,952
101	Part 2	10 days	287,98,952
102	**19th Floor**		
103	Part 1	10 days	287,98,952
104	Part 2	10 days	287,98,952
ID	**Activity Name**	**Normal Duration**	**Normal Cost**
105	**20th Floor**		
106	Part 1	10 days	287,98,952
107	Part 2	10 days	287,98,952
108	**21st Floor**		
109	Part 1	10 days	287,98,952
110	Part 2	10 days	287,98,952
111	**22nd Floor**		
112	Part 1	10 days	287,98,952
113	Part 2	10 days	287,98,952
114	Terrace Parapet	15 days	30,12,097
115	**OHT & LMR**		
116	Bottom slab	15 days	279,19,526
117	Top Slab	15 days	279,19,526

C. Methodology:

The Methodology adopted to crash the project to answer the Problem Statement consequently solving the Time-Cost-Quality Trade-off is depicted in the following points.

1) ***Using Microsoft Project to plan & schedule the project.***
   - A myriad of details are considered in planning how to coordinate all the RCC activities, in developing a realistic schedule. Of the many Project Management softwares, Microsoft Project is the most commonly used software to deal with all the data needed to develop schedule information.
   - The various activities are linked by the software in terms of their predecessors and successors.
   - Once completed, the total time required to complete the project is displayed thus answering Question 1 in the preceding section.

2) ***Using Microsoft Excel to schedule the project with CPM***
   - Each activity is scheduled by calculating its earliest & latest times (ES/EF/LS/LF) in MS Excel with the help of specific formulae thus answering Question 2.
   - The slack for an activity is the difference between its latest finish time and its earliest finish time. Thus knowing the earliest & latest times of each activity, their corresponding slack is calculated. Those activities with 0 slack will be classified as Critical activities.

3) ***Using Microsoft Excel Solver to crash the project and solve the Time-Cost-Quality Tradeoffs***
   - The problem of finding the least expensive way of crashing activities and the consequent Time-Cost-Quality Trade-off can be rephrased in a form more familiar to Microsoft Excel Sheet and solved using Microsoft Excel Solver Add-in. This section provides the answer to Question 3.

III. PROJECT CRASHING

A. Using Microsoft Excel:

The calculations for scheduling (ES, LS, slack, etc.) are set up in Microsoft Excel. They require use of the "min" and "max" functions and (to identify the critical path) the "if" function.

The following columns are imported to Microsoft Excel from Microsoft Project:

- Activity ID
- Activity Description
- Normal Duration
- Normal Cost
- The Immediate Predecessors
- The Immediate Successors

The following columns are then set up along with the above:

- ES, EF, LS, LF (For Each Activity)
- Crash Duration
- Crash Cost
- Crash Quality
- Maximum Crash Duration
- Cost Slope or Crash cost/day
- Quality Slope or Crash quality/day
- Quality Intercept
- Days to crash
- Realised time
- Quality Function qF
- Slack
- Critical (1 for Yes & 0 otherwise).

If there are two (or more) activities with no successors, it helps (for the setup) to add a "Finish" activity (all activities with no successors are predecessors of "Finish", duration is 0) but this is not required. Similarly, if there are two or more activities with no predecessors, it helps to add a "Start" activity (all activities without predecessors are successors of "Start", duration is 0).

❖ Filling in the columns:

First five columns are just the imported information on the activities from Microsoft Project.

1) ***Forward Pass for "Early" Times (ES; EF):***

In the column for ES the entry is always "=max(the EF entries for the immediate predecessors { separated by commas})" . The immediate predecessors are the nodes listed in the "Predecessors" column. In the EF column all entries are "= cell with ES + cell with Realised Time".

For the "Finish" node (if there is one) ES is "=max(all EF entries)"

2) ***Backward Pass for "Late" Times (LS; LF):***

In the LS column, the entry is "= cell containing LF - cell containing Realised Time"

In the LF column, the entry is "= min(the LS entries for all the immediate successors { separated by commas})"

The immediate successors of an activity are all the activities that have the activity in their "predecessors" list) [If you don't have a "Finish" node you need to remember that for an activity that has no successors, the LF entry is "=max(all EF entries)"

3) ***Slack :***

Slack is "=cell for LF - cell for EF" (or = cell for LS - cell for ES)

4) Critical:

Critical is "=IF(slack=0,"1","0")". This will put "1" in the cell if "slack = 0" is true and "0" if it is not. Finish time is "= EF of the "Finish" node" if there is a Finish node, or "= max(all EF entries)". Use the mouse to select the range of all EF entries.

5) Finish-to-Start (F-S):

Finish-to-Start (F-S) is the most commonly used Task relationship and is by default used by Microsoft Project to link the predecessors and successors unless specified otherwise. Complications may arise if there are different Task Relationships involved such as Start-to-Start (S-S), Start-to-Finish (S-F) & Finish-to-Finish (F-F). For this project there are a number of activities linked with S-S relationship. Thus the calculations of ES, LS & LF, for these activities, differ as follows:

- In the column for ES the entry is now "=max(the ES entries for the immediate predecessors { separated by commas})". If the predecessor has a lag value (example see Table II. Activity 5 has a predecessor relationship of 4SS+2days), it is added to the formula and if the predecessor has a lead value, it is subtracted from the formula.
- In the LS column, the entry is now "= min(the LS entries for all the immediate successors { separated by commas})". If the successor has a lead value (example see Table II. Activity 5 has a successor relationship of 6SS+5days), it is subtracted from the formula and if the successor has a lag value, it is added to the formula.
- In the LF column, the entry is now "= cell containing LS + cell containing Realised Time"

Table II:
Snippet Of The Main Schedule (Start-To-Start)

ID	Activity Name	Prede-cessors	Succes-sors	ES	EF	LS	LF
4	PCC below footings	-	5SS+2d	0	55	0	55
5	Reinfor--cement Fixing	4SS+2d	6SS+5d	2	58	2	58
6	Shutteri--ng	5SS+5d	7SS+3d	7	59	7	59

❖ Activity Crash Time, Cost & Quality:

According to the site engineers, the regular working time of workers is 8 hours a day for 7 days a week from 9:00am to 6:00pm with 1 hr lunch. According to the project managers, the only way activities can be accelerated is through using overtime. Since the maximum overtime allowed is 6 hours on top of the regular 8-hour working day, (from 8:00am to 12:00am, 14hrs a day) activities may be crashed on average at a ratio of 4:7 (i.e. Regular 8/ Overtime 14). The results are the maximum crash durations used. Site managers also believed that when activities need to be crashed, the cost increase is mostly due to the double rate for overtime. As consequence, they had no problem in accepting the assumption of linear relationship between cost escalation and time crashed, which is fundamental in the Babu and Suresh method. The performance quality expected under the normal conditions is assumed to be at 100% level for each activity. This assumption reflects the research objective of investigating only the impact of the time/cost factor, and not any other influence, on the project's overall quality. Babu and Suresh also consider the average of quality levels attained at the activities as the overall project quality objective. Two of the major findings in Khang and Myint (1999) were that `quality reduction due to overtime is negligible and cannot exceed 2±3%, even if the maximum amount of overtime is used' and that 'quality measure will decrease as a linear function of activity completion time from the normal value of 1.00 to its lower bound. The results obtained after following these assumptions are the crash qualities used.

Thus, the necessary base data are estimated containing the project's best estimates of its activity parameters.

Maximum crash time for each activity has been calculated by the following formula:
Maximum crash duration = Normal Duration – Crash Duration

Cost slope indicating the cost of crashing per day is calculated as:
Crash cost/day = (Crash cost – Normal cost)/ Maximum crash duration

Crash cost/day of some activities (36 & 45) is zero since they have no scope of being crashed. Hence, they are edited to a large number such as 10000000,00,000, to steer the software away from these values.

Similarly, Quality slope indicating the Quality crashed per day is calculated as:
Crash Quality/day = (Crash Quality – Normal Quality)/ Maximum crash duration

To calculate the Quality Function (qF) for each activity, we need to be familiar with the basic equation of a line: $y = mx + b$, where m is the slope and b is the intercept. Here y is our dependent variable which is the Quality Function (qF) and x is our independent variable which is the Realized Time.

The Realized is nothing but the number of days available after crashing which is calculated by:
Realized time = Normal duration – Days to crash

Initially, the days to crash are set to 0 which gives the value of realized time = normal duration. The ES/EF/LS/LF times are formulated using this realized time so that these times are revised every time an activity is crashed. Doing so, the Project Completion Time TF is obtained which is equal to 451 days.

Total Cost of project CF is calculated using the "SUMPRODUCT" function in Excel. The entry is "=SUMPRODUCT('days to be crashed' range,'maximum crash duration' range)". Using this formula gives the Total Cost of Rs 134,39,21,406.

Overall quality of project QF is calculated using the "SUM" function in Excel. The entry is "=(SUM ('qF' range))/N", where N is the total number of activities. Using this formula gives the Overall Project Quality of 100%

This will be the Base data to be used while using Microsoft Excel Solver add-in.

B. Using Microsoft Excel Solver:

To calculate the crashing of activities leading to the Time-Cost-Quality Trade-off has been undertaken in Microsoft Excel using the Excel add-in Solver. This add-in greatly aids in solving the complex crashing problem within minutes provided the input data is correctly inserted.

Once the solver is open, in the solver parameter dialogue box, (see Figure 1) the data required is carefully input.

1) In the 'Set Target Cell' box, the objective cell is input. The objective cell in this case is the Project Overall Quality. Our objective is to keep the Overall Quality at a maximum, hence select 'MAX'
2) In the 'By Changing Cells' box, the cells which will be varied throughout the course of the crashing process is entered. In this case, it is the column containing days to be crashed.
3) In the 'Subject to the Constraints' box, the constraints are entered. (See Figure 2)

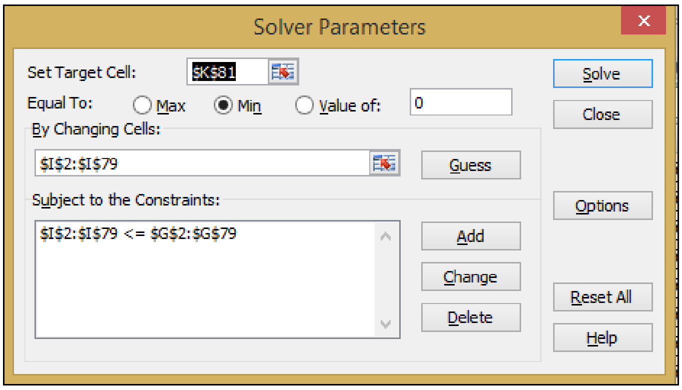

Fig 1: Solver Parameter Dialouge Box

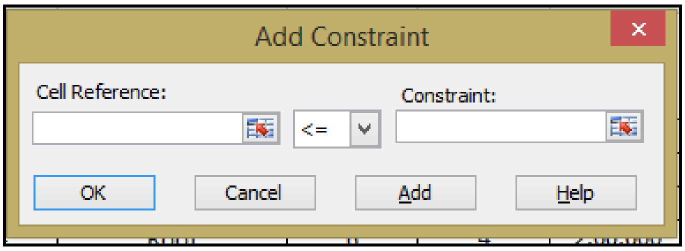

Fig 2: Solver Constraint Dialouge Box

i. Days to be crashed <= Maximum crash time

Under the cell reference, the entire range of days to be crashed is input & under constraint the entire range of maximum crash time is input.

ii. TF <= T'

iii. CF = C'

Where, T' are the lower bound values (due dates) for Project Completion Time TF and C' are the upper bound (budget constraints) for the Total Project Cost CF.

The lower bound values for completion times were allowed to vary from the maximum crash time of 282 days to normal completion time of 451 days, in increments of 20 days. The upper bound values of Total Project Cost were allowed to vary from normal cost of Rs 134.4 crores to the crash cost of Rs 240 crores, in increments of Rs 30 crores.

The days to be crashed are set to zero and all the data in entered in solver.

4) Next step importantly, the solver is closed. The input values in days to be crashed are edited to maximum crash duration. This automatically gives us the result depicting the latest finish time if all the activities are fully crashed, which is 288 days, costing Rs 8594935,26,550.

5) The days to crash are again edited to maximum crash durations and Solver is opened again and given the command to Solve, repeatedly using different values for the goal constraints of Time & Cost.

II. TIME-COST-QUALITY TRADEOFF

In particular, the following major findings can be noted:

A. Normal Duration, Cost & Quality Without Crashing:

1) Total Project Duration TF = 451 days
2) Total Cost of Project CF = Rs 134,39,21,406
3) Project Overall Quality QF = 100%

B. Maximum Crashed Duration, Cost & Quality:

1) Maximum Crash Duration = 288 days
2) Total Project Cost CF = Rs 8594935,26,550
3) Project Overall Quality QF = 91%

C. Optimum Quality When Duration & Cost are bound:

The computational results of this model are summarised in Table 3. In order to help managers to gain better insight of the trade-off among time, cost and quality factors of the project, the output of the model is re-organized by quality requirements. Wherever an increase in budget is not accompanied by a reduction in completion time, only the minimum budget required for that time is recorded. The results are summarized in Table IV and Figure 3.

III.CONCLUSIONS

- The total time required to complete the project if no delays occur is 451 days, at a total cost of Rs 134,39,21,406 and at 100% quality
- If all the activities were to be fully crashed instead, then a similar calculation would depict that the earliest the project can be completed is in only 282 days. But the prohibitive cost & quality reduction of doing this would be Rs 8594935, 26,550 & 91% respectively. Fully crashing all activities clearly is not a viable option.
- Analysing the results depicted in Table IV & Figure 3, it is now clear that managers may not expect to crash the project completion time below 420 days without compromising the high quality level of 98% or running to an exceedingly high cost.
- Similarly, if 95% average project quality is the performance that can be accepted, then trying to complete the project in less than 380 days may be very expensive.
- Crashing of any project must be undertaken only when the benefits received from crashing are more than the actual cost of crashing.
- The Problem of Time-Cost-Quality Trade-off is unique to every project and cannot be applied as a general rule. Project managers need to carefully understand the Time-Cost-Quality Trade-off of the project before deciding on whether or not to crash it.

Table III: Optimum Quality When Time & Cost Are Bound

	Upper Bound on C (in crores)					
Lower bound on T (in days)	**134.40**	**160.00**	**190.00**	**220.00**	**235.00**	**240.00**
282	NF	NF	NF	NF	NF	NF
300	NF	NF	NF	92%	92%	92%
320	NF	NF	NF	93%	93%	93%
340	NF	NF	93%	94%	94%	94%
350	NF	NF	93%	94%	94%	94%
360	NF	NF	94%	94%	95%	95%
380	NF	95%	95%	95%	95%	95%
400	NF	97%	97%	97%	97%	97%
420	NF	98%	100%	100%	100%	100%
440	NF	100%	100%	100%	100%	100%

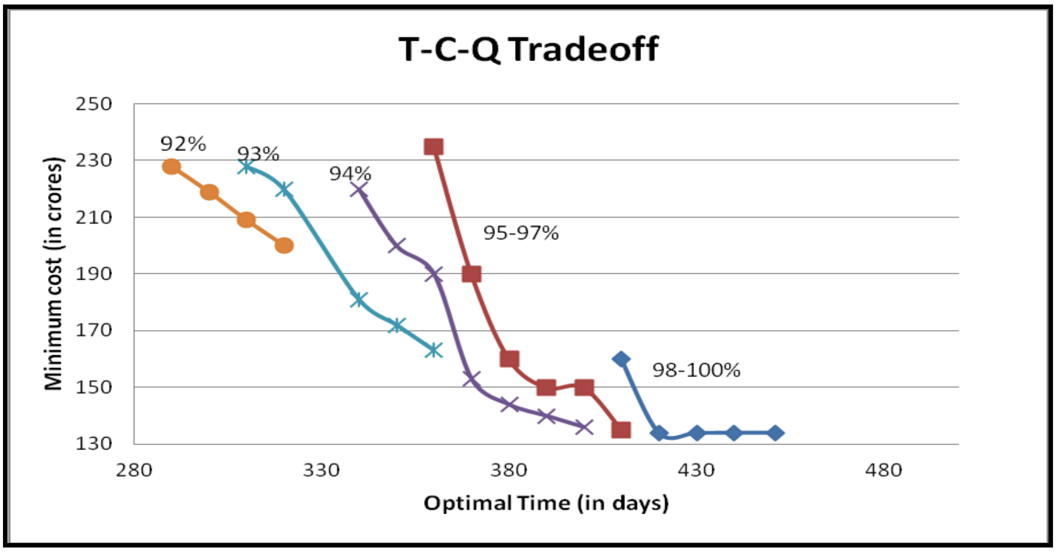

Fig 3: Time-Cost-Quality trade-off Showing Different Quality Levels

TABLE IV:
TIME-COST-QUALITY TRADE-OFF SHOWING DIFFERENT QUALITY LEVELS

Optimum Duration	Minimum Cost	Quality level
451	134.4	100%
440	160	
420	190	
420	160	98%
400	160	97%
380	160	95%
360	235	
360	190	94%
350	220	
350	190	93%
320	220	
300	220	92%

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