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Time, cost and quality trade-off in project management: a case study

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In 1996, Babu and Suresh proposed a framework to study the trade-off among time, cost and quality using three inter-related linear programming models. This paper describes our attempt to apply the method to an actual cement factory construction project. The purpose is to evaluate the practical applicability of the method by highlighting the managerial insights gained, as well as pointing out key problems and difficulties faced. As consequence, the paper helps practicing project engineers to have realistic expectations of the method. It also provides suggestions to overcome some practical problems if the method is to be applied in real industrial projects. © 1999 Elsevier Science Ltd and IPMA. All rights reserved

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Introduction

The critical path method (CPM) provides not only an excellent way of calculating the shortest completion time and the critical activities for a project, but also a framework to analyze the time/cost trade-off. In practice, however, one of the critical measures of project success is the quality of its performance that may be affected by attempt to crash the completion time with additional budget[1,2]. In this context, the traditional CPM method is inadequate to help the project manager make informed decisions on project progress and performance. Many attempts have been recorded in the literature to improve the method since its inception in the late 1950s[3]. However, most of this research either focused on improving the efficiency of the project-crashing algorithm[4–8], or on relaxing on the assumption of the linear relationship between cost and time factors[9–11]. In 1996, Babu and Suresh[12] proposed a new method to study the tradeoff among time, cost and quality using three inter-related linear programming models. Their approach is based on the linear relationship among the project cost, the quality measure and the project completion time. The method is illustrated with a small textbook example taken from Hillier and Lieberman[13].

This paper describes an attempt to apply the Babu and Suresh method to an actual cement factory construction project in Thailand. With the purpose of evaluating the practical applicability of the method, the basic assumptions are investigated, major problems in estimating input parameters are pointed out, and the resulting managerial insights are highlighted. As consequence, the paper helps practicing project engineers to have realistic expectations of the method. It also provides suggestions to overcome various practical problems if the method is to be applied in real industrial projects. This research also validates with real data most of the conceptual findings by Babu and Suresh in their original work.

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Review of Babu and Suresh cost–time–quality trade-off models

Babu and Suresh developed their method by assuming that the project activities and their precedence relationships are determined. Each activity has a normal time of completion and a crash time of completion. Associated with the normal time are normal cost and normal performance quality, and with crash time are crash cost and crash quality. It is assumed that the cost and quality of an activity vary as linear functions of the completion time. Given individual activity completion times, the total project completion time can then be calculated using the traditional CPM method. The total cost is simply the sum of individual activity costs, and the total project quality is measured by the average of the individual activity quality measures.

Babu and Suresh suggest three optimization models as a framework to analyze the trade-off among the cost, time and quality factors of a project. In order to formulate these models in the familiar linear programming (LP) format, the activity-on-arc (AOC) network convention and the following notation will be used:

M: Number of events
N: Number of activities

Y_i: Earliest time of event i (i = 1,2,...,M)
X_{ij}: Duration of activity (ij) (X_{ij} and Y_i are decision variables)
t_{ij}: Normal time for activity (i,j)
t'_{ij}: Crash time for activity (i,j) ($t_{ij} \geq t'_{ij} \geq 0$)
c_{ij}: Normal cost for activity (i,j)
c'_{ij}: Crash cost for activity (i,j) ($c'_{ij} \geq c_{ij} \geq 0$)
q_{ij}: Normal quality for activity (i,j)
q'_{ij}: Crash quality for activity (i,j) ($q_{ij} \geq q'_{ij} \geq 0$).

Notice that a dummy activity can be indicated by letting $t_{ij} = t'_{ij} = 0$. The constraints common to all the LP problems can then be summarized as follows:

(a) The project is started at time zero.

$$Y_1 = 0 \quad (1)$$

(b) Each activity completion time X_{ij} is bounded from above by the normal time, and from below by the crash time:

$$t_{ij} \geq X_{ij} \geq t'_{ij} \quad (2)$$

(c) For each activity (i,j),

$$Y_i + X_{ij} - Y_j \leq 0 \quad (3)$$

The objective function for the first LP model is the project completion time that is simply the earliest time of the last 'finish' event:

$$TF = Y_M$$

For the second model, the objective function is the total cost of the project. By assuming the linear relationship of the activity cost and completion time, the total project cost is estimated as a linear function of the individual activity times:

$$CF = \sum_{(i,j)} (A_{ij} + B_{ij} \times X_{ij}),$$

where $B_{ij} = (c'_{ij} - c_{ij})/(t_{ij} - t'_{ij})$ and $A_{ij} = c'_{ij} - B_{ij} \times t'_{ij}$ are the slope and intercept of the cost curve for activity (i,j). For the third model, the objective function is the project's overall quality that is calculated as the average of the individual activity qualities, that is

$$QF = \sum_{(i,j)} (A'_{ij} + B'_{ij} \times X_{ij}),$$

where $B'_{ij} = (q_{ij} - q'_{ij})/(t_{ij} - t'_{ij})$ and $A'_{ij} = q'_{ij} - B'_{ij} \times t'_{ij}$ are the slope and intercept of the quality curve for activity (i,j).

Thus, assuming that T' and Q' are the lower bounds for project completion time TF and average quality QF, and C' is the upper bound for total cost CF, the models can be simply written as:

Model 1: Minimize TF subject to (1–3) and $CF \leq C'$ and $QF \geq Q'$;
Model 2: Minimize CF subject to (1–3) and $TF \leq T'$ and $QF \geq Q'$;
Model 3: Maximize QF subject to (1–3) and $CF \leq C'$ and $TF \leq T'$.

For different budget levels and the quality tolerances, the first model yields the corresponding shortest completion times, and thus provides a framework for the trade-off analysis by considering project completion time as a function of budget and quality constraints. In a similar way, the second model searches for the lowest cost to complete the project as a function of completion due dates and quality tolerance allowed, while the third model yields maximum overall project quality subject as a function of budget constraints and completion due date.

Case study and parameter estimation

TPI Polene Public Company Limited (TPIPL) is located about 134 km north of Bangkok, Thailand. The company currently operates three cement factories with an annual capacity of 9 million tons per annum. The fourth factory is now under construction and is expected to be in operation by 1998, which will bring the total cement capacity to 12.3 million tons per annum. The total cost for this new construction project is estimated to be baht 9.6 billion (or roughly US$375 million). The scope of work for the whole project is large and complex with 35 different sub-projects and more than 1000 separate activities. Partly because of this complexity, and partly due to the fact that the completion of the project is subject to a large number of exogenous factors, both economical and political, beyond the control of the top management, it was decided to focus this research on only one of its sub-projects. The sub-project chosen is one of erecting the Dopol pre-heater tower, which is the most time consuming and problematic sub-project in the whole factory construction project. In fact, the pre-heater tower erection is so important that its schedule is used by project engineers as the benchmark to adjust the schedule of all other sub-projects. It is believed that using this sub-project in evaluating the practical value of the method will not affect the validity of the conclusions.

The activities of the sub-project to erect the Dopol pre-heater tower can be grouped into 52 work packages under four main categories: civil work (leveling, excavation, foundation and construction), mechanical work (fabrication, erection, refractory and cold test run), electrical work (power distribution, substation and transformer, MCC control, cable rack installation, power supply) and automation (Plc cabinet, safety and local control). Each work package consists of numerous related specific activities that are normally carried out under a single supervisor or subcontractor. The work packages are identified so that activities of different work packages do not use the same resources at the same time, and therefore can be scheduled relatively independently. Care is taken that completion time and cost of individual work packages can be estimated relatively easily and accurately. The list of these work packages and their brief description is given in *Table 1*.

Estimating the relevant input parameters for work packages was probably the most time consuming task in applying the Babu and Suresh method to the sub-project under study. The work was done in close consultations with site managers. Below is described the way these parameters were estimated as well as the difficulties encountered.

Table 1 Works on Dopol preheater tower and the estimates parameters

Work-package	Brief description of work	t_{ij} (days)	t'_{ij} (days)	c_{ij} (million baht)	c'_{ij} (million baht)	q'_{ij}
A	Procurement of Rebars	33	22	5.50	8.25	0.90
B	Procurement of steel section, plates, pipes, etc.	33	22	58.40	87.60	0.90
C	Excavation	33	22	0.50	0.75	0.90
D	Foundation	33	22	6.50	9.75	0.95
E	Concrete columns to first floor (188 m)	22	15	3.40	5.10	0.95
F	Concrete floor and beams to first floor	22	15	3.50	5.25	0.95
G	Concrete columns to second floor (200m)	22	15	2.50	3.75	0.95
H	Fabrication of beams, steel floor and staircase (second floor)	44	29	1.09	1.63	0.83
I	Fabrication of kiln inlet and transaction piece	75	50	1.84	2.76	0.83
J	Erection of kiln inlet and transaction piece	75	50	1.10	1.65	0.85
K	Installation of beams, steel floor and staircase (second floor)	44	29	1.95	2.93	0.85
L	Fabrication of beams, steel floor and staircase (third floor)	55	37	2.22	3.34	0.83
M	Installation of steel structure to 3rd floor (217 m)	55	37	4.00	6.00	0.85
N	Erection of 1st stage cyclones and ducts between 3rd and 4th floors	30	20	1.80	2.70	0.85
O	Fabrication of 1st stage cyclones and ducts (3rd floor)	30	20	1.08	1.61	0.83
P	Refractory works (kiln inlet, transaction pieces, column ducts)	40	27	2.85	4.28	0.90
Q	Electrical works in 1st, 2nd and 3rd floors	40	27	2.50	3.75	0.70
R	Fabrication of beams, steel floor and staircase (4th and 5th floors)	55	37	3.15	4.73	0.83
S	Erection of beams, steel floor and staircase for 4th and 5th floors (251 m)	55	37	5.68	8.51	0.85
T	Erection of 2nd stage cyclones and transfer ducts	40	27	1.65	2.48	0.85
U	Fabrication of 2nd stage cyclones and transfer ducts	40	27	2.75	4.12	0.83
V	Refractory works at 1st stage cyclones and ducts	44	29	2.54	3.81	0.90
W	Fabrication of beams, steel floor and staircase (5th and 6th floors)	55	37	1.99	2.99	0.83
X	Erection of beams, steel floor and staircase (5th and 6th floors)	55	37	3.59	5.38	0.85
Y	Erection of 3rd stage cyclones	30	20	0.80	1.20	0.85
Z	Fabrication of 3rd stage cyclones and ducts	30	20	1.34	2.01	0.83
AA	Refractory works at 2nd stage cyclones and ducts	44	29	2.54	3.81	0.90
AB	Electrical and instrument cabling 4th and 5th floor	22	15	1.50	2.25	0.70
AC	Installation of 2 Poldos-feeding equipment in 1st floor	30	20	1.20	1.80	0.85
AD	Installation of shock blowers (M.E) in floors 1,2 and 3.	30	20	1.25	1.88	0.85
AE	Fabrication of beams, steel floor and staircase (6th and 7th floors)	55	37	1.59	2.39	0.83
AF	Erection of beams, steel floor and staircase for 6th and 7th floors (268 m)	55	37	2.87	4.30	0.85
AG	Erection of 4th stage cyclones on 6th floor	30	20	0.69	1.04	0.85
AH	Fabrication of 4th stage cyclones etc.	30	20	1.16	1.73	0.83
AI	Refractory works at 3rd stage cyclones and ducts	44	29	3.25	4.88	0.90
AJ	Electrical and instrument cable racks etc. (6th floor)	22	15	1.50	2.25	0.70
AK	Fabrication of beams, steel floor and staircase (7th and 8th floors)	72	48	1.54	2.31	0.83
AL	Erection of beams, steel floor and staircase for 7th and 8th floors (291 m)	72	48	2.77	4.16	0.85
AM	Erection of 5th stage cyclones on 7th floor	40	27	0.62	0.93	0.85
AN	Fabrication of 5th stage cyclones and ducts	40	27	1.04	1.55	0.83
AO	Refractory works on 4th stage cyclones and ducts	44	29	3.25	4.88	0.90
AP	Fabrication of ladder, platform, stairs,beams for 8th floor	55	37	1.23	1.85	0.83
AQ	Erection of steel structures for 8th floor	55	37	2.22	3.33	0.85
AR	Erection of 6th stage cyclones on 8th floor	40	27	1.19	1.79	0.85
AS	Fabrication of 6th stage cyclones on 8th floor	40	27	1.98	2.97	0.83
AT	Refractory works on 5th stage cyclones and ducts	44	29	1.66	2.49	0.90
AU	Fabrication of second gas duct	165	111	3.55	5.32	0.83
AV	Refractory work on 6th stage cyclones completed	66	44	3.26	4.90	0.90
AW	Electrical and instrument cables on 7th floor	30	20	1.50	2.25	0.70
AX	Installation of local instruments	88	59	5.23	7.85	0.85
AY	Insulation for gas ducts and 6th stage cyclones connection	66	44	2.28	3.62	0.85
AZ	Readying for test run	5	3	0.50	0.75	0.85

Normal time cost and quality parameters

The time and cost parameters under assumed normal conditions were easiest to estimate. In fact, the normal completion time of activity was taken from the existing project schedule that had been prepared by project engineers with care taken to all technical details. For the purpose of studying the inter-relationship among the cost, time and quality dimensions of the project in crashing the activities, all fixed costs of equipment and materials procurement, and the overhead were excluded from these cost parameters. In fact, all site managers and engineers believed that these costs, although being a major part of the total cost, were not affected by decisions of crashing the project activities. Thus the cost data used in the calculations (see also *Table 1*) include only the variable costs of which labour cost is the major component. Since the relative quality reduction due to crashing activities is the focus of interest in this research, 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.

Crashing time, cost and quality

Most of the work at the pre-heater tower is labour intensive with relatively clear definition. As it is typical for construction sites in Thailand, the number of workers working 6 days a week at the project is already at the maximum due to the limited work area. Thus, according to the managers, the only way activities can be accelerated is through using overtime. Since the maximum overtime allowed is 4 hours on top of the regular 8-hour working day, activities may be crashed on average at a ratio of 2:3. These crash times were then adjusted for each of the 52 work-packages taking into account the possibility that workers may sometimes be asked to work on Sunday also, and that some work would permit less hours of overtime due to lighting conditions and safety reasons. The results are the maximum crash times t'_{ij} used in the LP models. Site managers also believed that when activities need 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 estimation of the quality reduction due to crashing was more difficult and elaborate. There were two major obstacles in arriving at an acceptable measurement of quality reduction. First, and not surprisingly, it was found that the practicing managers and engineers were very sensitive to the idea that the quality of the project could be compromised at all by crashing. Second, the quality of an activity can be usually measured only by subjectively using managers' judgement. In a few cases when quality can be determined quantitatively and objectively using technical specifications, these specifications were to be adhered to rather strictly, and the quality measure was not noticeably affected by the use of overtime. The common reaction was that 'quality reduction due to overtime is negligible and cannot exceed 2–3%, even if the maximum amount of overtime is used'. With the objective of arriving at workable estimates of quality reductions in project activities due to crashing, the following principles were agreed:

1. In interpreting the results of the models, it is not the absolute value of the quality measure that is relevant, but the relative quality values of the individual activities when crashing is performed.
2. These relative values should reflect two considerations:
   - Some works (such as painting works) are more prone to the measurable quality reduction when crashed;
   - Some works (such as welding or electrical works) are so important and critical that a minor reduction in quality may seriously compromise the whole project performance.

     In both cases, crashing should induce a relatively large reduction in the quality measures of the activities.
3. If a work-package has more than one activity then its quality is measured as the weighted average of the individual activities' quality where the weights are proportional to the contractual values of the activities.

Based on this common framework, the researchers and the managers together compared the individual activities to estimate the relative quality reductions due to crashing. The last column of *Table 1* is the result of this time consuming process. The numbers in that column indicate the relative, and at times subjective, assessment of the quality of the individual project activities when maximum crash is performed. It is presumed then that the quality measure will decrease as a linear function of activity completion time from the normal value of 1.00 to this lower bound.

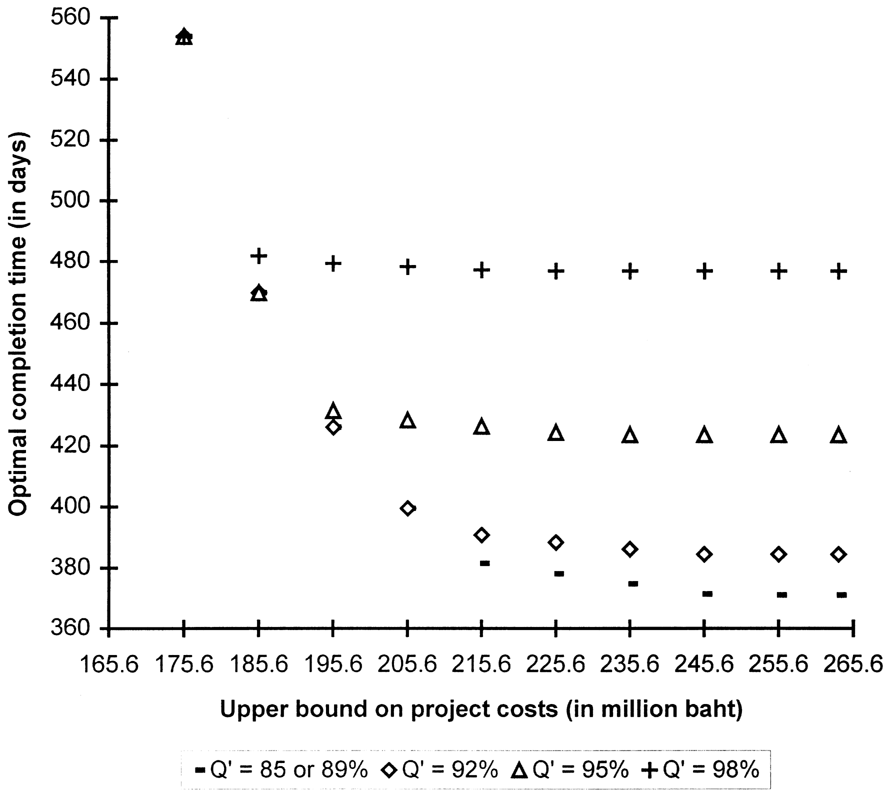

Figure 1 Optimal completion time when costs and quality are bounded

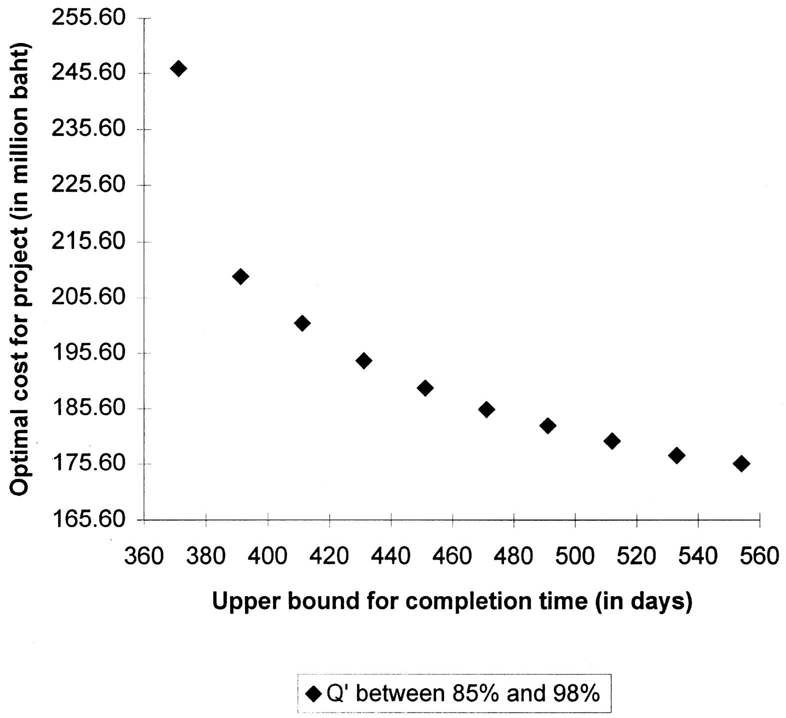

Figure 2 Optimal cost when completion time and average quality are bounded

Analysis of computational results

Once the parameters are estimated, the computation of the three models, using software LINDO (version 5.1), is simple since the size of the LP problems is relatively small (104 variables and 231 constraints for each model). All these problems were solved repeatedly using different values for the goal constraints in cost, time and quality. The maximum budget varied with increments of 10 million baht—except for the last increment—from the normal cost of 175.60 million baht to the maximum crash cost of 263.60 million baht. The lower bound for completion time was allowed to change in increments of 20 days—or 21 days for the last three increments—from the maximum crash time of 371 days to the normal time of 554 days. Five different quality levels were considered in the models: 85%, 89%, 92%, 95% and 98%.

The computational results of the three models are summarized in *Figures 1–3* and *Tables 2–4* which bear much similarity to the corresponding results obtained by Babu and Suresh with their textbook example. In particular, the following major findings can be noted:

- For each given quality level, there exists a budget threshold beyond which there would be of little value to increase budget in the hope of expediting further project completion. These thresholds are given in *Figure 1* as 185.60 million baht at a 98% quality allowance, 195.60 million baht at a 95% quality allowance, and 215.60 million baht at a 92% quality allowance. The corresponding completion times are 482 days, 431 days and 391 days, respect-

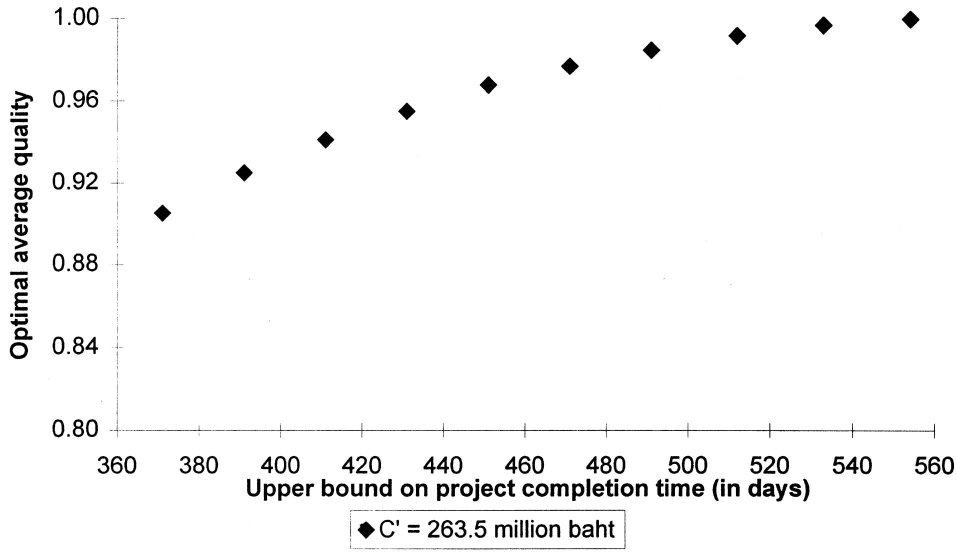

Figure 3 Optimal average quality when cost and completion time are bounded

Table 2 Optimal completion time (in days) when costs and quality are bounded

	Lower bound on project quality				
Upper bound on project costs (million baht)	0.85	0.89	0.92	0.95	0.98
175.6	554	554	554	554	554
185.6	470	470	470	470	482
195.6	426	426	426	431	479
205.6	400	400	400	428	478
215.6	381	381	391	426	477
225.6	378	378	388	424	477
235.6	375	375	386	424	477
245.6	371	371	385	424	477
255.6	371	371	385	424	477
263.6	371	371	385	424	477

Table 3 Optimal project cost when completion time and average quality are bounded

	Lower bound on project quality				
Upper bound on completion time (in days)	0.85	0.89	0.92	0.95	0.98
371	246.48	246.48	INF	INF	INF
391	209.42	209.42	214.50	INF	INF
411	200.97	200.97	200.97	INF	INF
431	194.21	194.21	194.21	196.26	INF
451	189.32	189.32	189.32	189.32	INF
471	185.41	185.41	185.41	185.41	INF
491	182.48	182.48	182.48	182.48	182.49
512	179.67	179.67	179.67	179.67	179.67
533	177.08	177.08	177.08	177.08	177.08
554	175.60	175.60	175.60	175.60	175.60

ively. At the lower quality levels of 89% and 85%, the thresholds are not as sharp as with the higher quality tolerances.

- If the average quality requirement is decreased, these budget thresholds, which can be interpreted as the practical limiting costs for crashing, will increase, which in turn allows for a further reduction in project completion time.
- Project cost is almost independent of the quality requirement and therefore, the cost/time curves in *Figure 3* coincide for all quality levels. This fact is not surprising because the performance quality at each activity was assumed to be a function of the time factor only.
- There is a critical value for project completion time, beyond which it would be extremely expensive to crash further. *Figure 2* indicates that this critical value is around 400 days.

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 Model 1 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 *Tables 5* and *Figure 4*. It is now clear that managers may not expect to crash the project completion time below 482 days without compromising the high quality level of 98%

Table 4 Optimal average quality when cost and completion time are bounded

	Upper bound on project costs (in million baht)									
Lower bound on completion time (in days)	175.6	185.6	195.6	205.6	215.6	225.6	235.6	245.6	255.6	263.6
371	INF	INF	INF	INF	INF	INF	INF	0.91	0.91	0.91
391	INF	INF	INF	INF	0.92	0.92	0.92	0.93	0.93	0.93
411	INF	INF	INF	0.94	0.94	0.94	0.94	0.94	0.94	0.94
431	INF	INF	0.95	0.95	0.95	0.96	0.96	0.96	0.96	0.96
451	INF	INF	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97
471	INF	0.97	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
491	INF	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
512	INF	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
533	INF	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
554	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table 5 Trade-off among optimal cost, time and quality level

Optimal duration (in days)	Minimum cost (in million baht)	Quality level
554	175.6	0.98
482	185.6	
479	195.6	
478	205.6	
477	215.6	
477	225.6	
470	185.6	0.95
431	195.6	
428	205.6	
426	215.6	
424	225.6	
424	235.6	
426	195.6	0.92
399	205.6	
391	215.6	
388	225.6	
386	235.6	
384	245.6	
381	215.6	0.85–0.89
378	225.6	
375	235.6	
371	245.6	
371	255.6	

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 431 days may be very expensive.

Assessment of the method and conclusions

The linear programming models proposed by Babu and Suresh are conceptually easy to understand, and computationally easy to solve. All managers and engineers are interested in the possibility of incorporating performance quality in the time and cost scheduling. The results obtained, when presented using proper graphics, provide insightful information that can help the managers in making trade-off decisions. At the early stage of the cement factory construction project when the research was conducted, the goal of completing the construction in time was the most important for the managers. Thus, Model 1 was judged as the most relevant and interesting. However, it is possible to foresee a situation where Model 2 becomes prominent, especially when some cost overrun has occurred in the project and the task of minimizing expenditures is of the top priority. In any case, the two models 1 and 2 are dual in the linear programming sense, and can always be considered together with quality levels as parameters. Model 3, although playing a rather symmetric role with the other two, is less appealing to practical managers and engineers. The main objection to this model is that the quality measurements are sometimes too subjective and inaccurate to be considered as an objective function in an LP formulation. At the same time, it can be observed that, while all managers, understandably, are sensitive to the issue of quality reduction due to crashing work, they are also reluctant to consider improving an already acceptable quality level at extra expenses or by delaying the project completion.

As already pointed out by Babu and Suresh, the solutions of the models support the common intuition regarding effects of time, cost and quality in project management. The most valuable finding to managers participating in the research, and probably a surprising one for some, is the recognition of the existence of the different budget thresholds for the time/cost curve at different quality levels. These thresholds, not mentioned by Babu and Suresh, are explicitly presented in *Figure 4*, and judged as most useful in helping managers making trade-off decisions.

The managers involved in this research consider as reasonable the assumption of linear relationship between cost and time. The fact that crashing this particular project was practically possible only through overtime not only made the assumption readily accep-

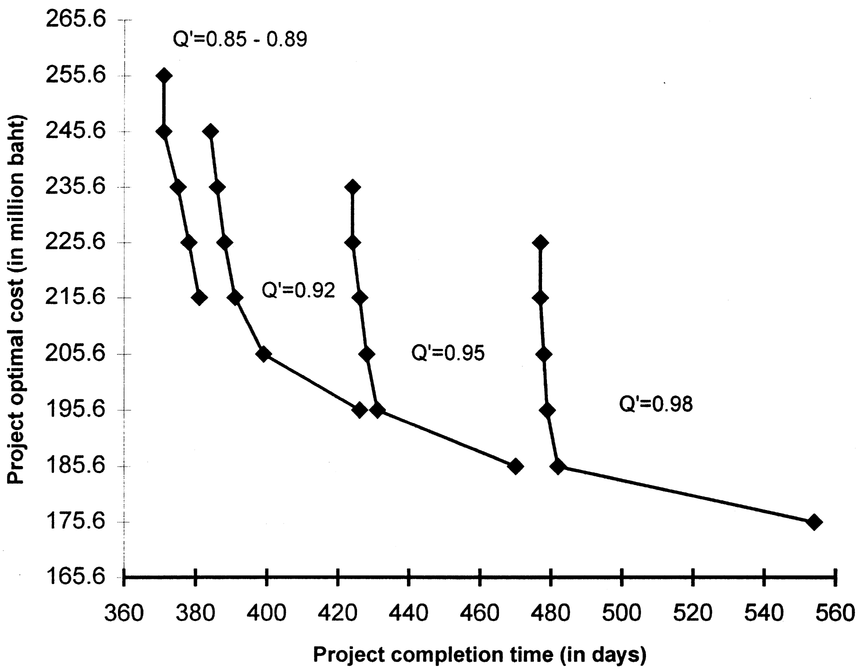

Figure 4 Trade-off among optimal cost, time and quality requirement

table, but also facilitated estimating the necessary parameters. The linearity assumption between quality and time is more problematic. In fact, the most difficult, and probably most controversial, task in applying the method in the case project was to assess the quality reduction associated with crashing. In the current research, this is achieved, to a certain degree of satisfaction of both the researchers and practitioners, through the framework outlined in the chapter on parameter estimation. Even then, it is recognized that the quality measures at best reflect only relative performance levels of different activities with different crashing decisions. The difficulty also highlights a major limitation of the method: in all practically justifiable measurements of quality, only a very small portion bears direct relation with crashing decisions. Thus, the quality factor considered in the models accounts for only a small, and unfortunately usually not the most relevant, part of the performance of managerial interest. This leads to an interesting research question of finding a more holistic measurement for performance quality, and a more realistic model to describe the relationship among quality of individual activities, and therefore of the whole project, and the budget and time allowed.

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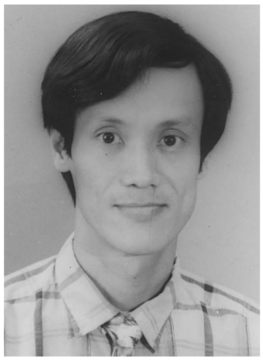

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