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Historical Data-Based and Simulation-Aided Probabilistic Approach for Cost-Time Control

Heedae Park, Seung Heon Han, Donghoon Yeo
Department of Civil Engineering, Yonsei University, Seoul, Korea
parkheedae@yonsei.ac.kr, shh6018@yonsei.ac.kr, totwd@yonsei.ac.kr

Bo Seong Kang
Republic of Korea Navy, Daejeon, Korea (Foremerly master of Yonsei University)
bo0tes@hanmail.net

Abstract
Cost and time control has long been an essential part of construction management, which is considered a series of decision-making processes based on uncertain site conditions as well as periodic feedback with contractual requirements. Traditionally, a number of researchers have sought a way to provide feasible methods for such types of decision-making, which is largely attributed to deterministic approaches that lack the delivery of project uncertainties. The current probabilistic method, however, still leads to a shortage of practical applications because, more often than not, the probability patterns are less connected with real performances and, further, the actual properties of a given activity are not adequately addressed. In addition, such methods are frequently under attack due to the absence of methods for assessing alternative scenarios to improve as-is performance from the project manager's perspective. This study attempts to help narrow the gap in the current probabilistic approaches for cost-time analysis and scenario simulation. The reality of a probabilistic approach based on historical data accrued from each activity's performance is proposed. Then, the framework for extracting alternatives to enhance current performance is also presented through discrete event simulation as well as the project manager's experiential intuition. The benefit of the proposed approach is demonstrated through a case study.

Keywords
Probabilistic approach, Cost-time analysis, Discrete event simulation, Scenario analysis

1. Introduction

Construction projects are vulnerable to diverse conditions encompassing the uniqueness of each project, design error, change order, climate and differing site condition, and public resistance, so that variations in cost and time are inevitable for most cases. Therefore, a rational and logical cost-time management plan and a decision support tool are required to respond effectively to unpredictable conditions, and to complete a project successfully in the end. For that reason, cost and time control has long been an essential part of construction management, which is usually tied to a series of decision-making for addressing variable site conditions mentioned above as.

A number of studies have been conducted to provide feasible methods for such types of decision-making, for example, predicting the final cost and time at completion, optimizing the cost and time in a trade-off situation and allocating resources considering both time and cost constraints, just to name a few. With the

Critical Path Method (CPM) and Program Evaluation and Review Technique (PERT) at the head of the list, heuristic methods, mathematical programming models, and other algorithms were developed and applied to those managerial problems.

However, these methods are largely relied on deterministic approaches so that the methods lack the delivery of project uncertainties. The recent probabilistic method also leads to a shortage of practical applications because, more often than not, the probability distributions are less connected with real performances and, further, the actual properties of a given activity are not adequately addressed. Moreover, such methods are frequently under attack due to the absence of methods for assessing alternative scenarios to improve as-is performance from the project manager's perspective. This study aims to close the gap in current probabilistic approaches for cost-time analysis. A practical decision-making procedure is suggested with the reality of the probabilistic approach based on historical data accrued from each activity's previous performance. In addition, a framework for extracting alternatives to enhance current performance is also presented through productivity evaluation and discrete event simulation as well as the project manager's experiential intuition. The practical applicability and the benefits of the proposed approach are demonstrated through a case study of a grand bridge project in Korea, and the principles of the proposed approach for field staffs are also presented.

2. Research Background

Cost and time management of a construction project inherently involves uncertainties because such management relies on the evaluation of current performance and projection of future state. Deterministic methodologies, therefore, have limitations in managing cost and time appropriately due to the lack of addressing uncertainties. The diverse uncertainties of construction projects can create cost overrun and time delay to complete each activity. Accordingly, a number of research papers have more focused on the probabilistic approach that applies probability distribution to estimate final cost and time, and other relevant studies. For example, Isidore and Back (2001) assigned uniform probability distributions to the cost and time of all activities in a project and calculated the range of the total cost and time through a Monte Carlo simulation of the CPM network. The study provided a suitable but not an optimal solution according to the confidence level. Feng *et al.*, (2000) proposed a genetic algorithm-aided simulation model for cost-time trade-off where the normal distribution was assigned to every variation of cost and time, and the alternative analysis for each activity was also attempted. However, this method is very different from practical situations because the authors focused more on the operation of the genetic algorithm, looking for an optimized combination rather than detailed methodology or a procedure to analyze alternatives. Moreover, both studies have limitations in assuring the reality of the probability distribution because they adopted a particular assumed probability distribution for all activities.

While research on cost-time optimization focused on seeking optimized combinations of cost and time that minimize the final cost, other research on predicting the final cost and time of construction projects has analyzed the trend of cost and time during the construction process based on the earned value. Barraza *et al*., (2004) proposed a progress-based stochastic S-curve that imports the probability concept to the cost and time variation along construction progress. They derived cost and time estimates at every 10% of construction progress through iterative simulations. Lee and Park (2005) developed stochastic project scheduling simulation software and proposed a methodology that predicts the behavior of the final construction cost through reflecting the randomly varying activity duration and changing overhead cost. However, both studies on cost-time prediction also have the limitation in that they applied arbitrary probability distribution, which fails to effectively reflect site conditions.

Common limitations of previous studies are similar to the following: arbitrary probability distributions such as uniform distribution, normal distribution, and triangular distribution are simply applied to every activity to reflect variations. This reduces consideration of the uncertainties of construction projects. In addition, alternative analysis that modifies construction methods and the production processes of activities to reduce the variations are not fully considered in most of the research; hence, there are differences with real construction projects and their practical affairs consequently. Therefore, this study can be worthwhile to overcome such limitations through proposing a probabilistic cost-time analysis model that ensures the practicality of the probability distributions of each activity's cost and time and promotes the effectiveness of alternative analysis in a practical manner.

3. Probabilistic Cost-Time Analysis

3.1 Cost-Time Analysis Framework

Since the cost-time analysis model in this study is developed based on the assumption that the historical cost and time records of every activity can be extracted from a real project, the model is applicable to a middle-phased project where an iterative process is in progress so that distributions of each activity's cost and time could be extracted from past records. The framework of the cost-time analysis is shown in Figure 1.

Since this study aims to develop a practical cost-time analysis model, reliable probability distributions of cost and time are required; thus, the performance measurement of each activity by the project supervisor is very important. Data such as labor, equipment, and the start and end points should be recorded based not on a project level but on the activity level in a CPM network in further detail. From the collected data, the most suitable probability distributions for each activity's cost and time are extracted using data distribution fitting software, such as BestFit®. Each activity's attributes, including a probability distribution, are used in the simulation model.

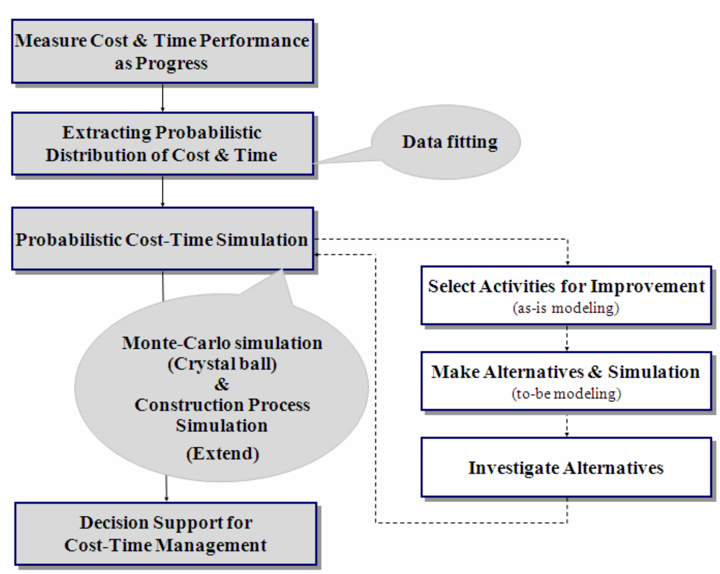


Figure 1: Cost-Time Analysis Framework

3.2 Probabilistic Cost-Time Simulation Model

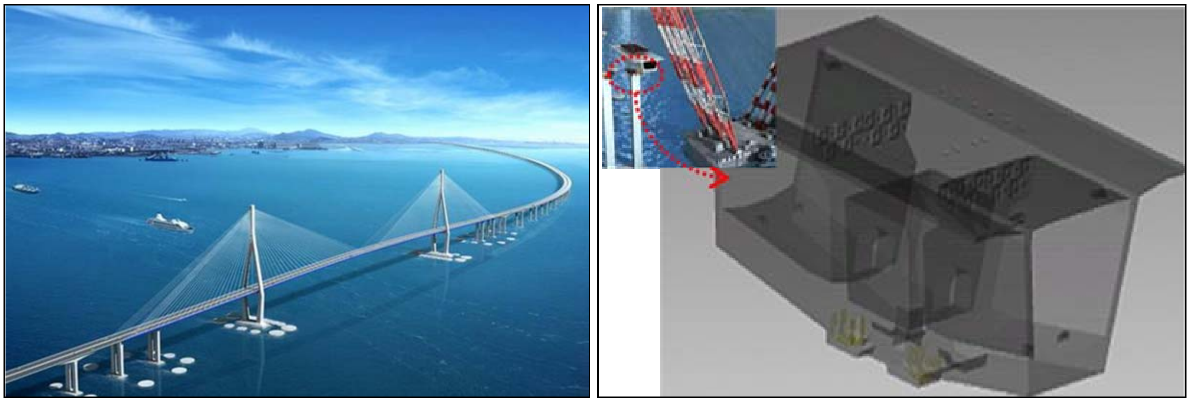
The probabilistic cost-time simulation model is composed of three stages: as-is modeling and simulation, devising alternatives and to-be modeling and evaluating the to-be model (refer to Figure 1). Based on the past records and probability distributions of cost and time, a prediction of the final cost and time in the CPM network is obtained through Monte Carlo simulation. This study used Crystal Ball®, risk analysis software that provides an estimate, its confidence level, and the possibility of particular event outbreaks in the form of a spreadsheet. The results of the simulation enable the identification of possible duration change and the distribution of the required cost expenditure.

For effective cost-time management, identification of activities that significantly influence cost and time is indispensable, and the expected results of every alternative should also be analyzed. To this end, the model selects activities that have considerable influence on cost and time through the sensitivity analysis results from the simulation of the as-is situation. Then, activities that have a high potential to enter into the critical path are also selected as those requiring intensive control and improvement. Together with the identification, the following procedures are introduced for cost-time simulation: (1) measure the productivity of a target activity through work sampling and a crew balance study, (2) create alternatives by eliminating wasteful factors and improving the construction process, and (3) perform a simulation on the as-is state and the to-be state, and verify statistical feasibility with the t-test. Hence, application of the cost-time analysis model in this study is more applicable to iterative activities that accumulate enough past records However, not every activity in a construction project can simulate the construction process, and there are projects in which many independent activities are in progress at the same time; therefore, a site manager's decision making based on experience and intuition should be considered simultaneously.

4. Case Study

4.1 Summary of the Case Study Project

To demonstrate the applicability and benefits of the proposed approach, a case study of a bridge project in Korea is performed. This is a very large-scale project that is 21 kilometers long in total and connects Incheon International Airport and Songdo. The case project, Incheon Grand Bridge, is composed of a 12-kilometer-long marine bridge and a 9-kilometer-long connecting road. The span distance between the main pylons of the marine bridge is 800 meters; thus, this is the longest cable-stayed bridge in Korea and the 5th longest in the world. Figure 2(a) shows a bird's-eye view of Incheon Bridge. In this project, thousands of interrelated sites are in progress at the same time both on the sea and on the shore. Billions of dollars and tons of resources are invested; therefore, thorough and systematic cost-time control of each site and activity is essential. Specifically, a pre-stressed concrete box girder production factory is selected as the case study. This factory is located on the shore and produces box girders that will be installed on the upper part of piers by the free cantilever method. In further detail, this study focuses on the box girder production process to test a proposed time-cost analysis framework because it fits well in terms of the model restriction, the proper number of activities in the CPM network, and less cycle time for data collection.



(a) (b)

Figure 2: Case Study Project and Object Activities (Incheon Grand Bridge, 2008)

4.2 Data Collection and Assumptions

The production process of pre-stressed concrete box girder starts with the formwork and rebar installation of a Match Cast Block (MCB, see Figure 2(b)), which is pre-fabricated and then connects a grand block with a pier at the center of the floor. Thereafter, several activities such as formwork, rebar installation, and concrete pouring for lower and upper part of pre-stressed concrete box proceed iteratively. Detailed activities and operations are listed in Table 1. The authors collected the records of 15 box girders out of total 24, produced from May 2006 to December 2007.

Table 1: Activity and Operation List

Activity	Operation	Activity	Operation
A	Floor & outer wall rebar assembling	I	2nd concrete pouring
B	Floor formwork installation	J	Concrete curing & de-formwork
C	1st concrete pouring	K	MCB & outer formwork installation
D	Concrete curing	PA	Floor rebar pre-assembling
E	Wall rebar assembling	PB	Floor mold pre-assembling
F	Diaphragm rebar assembling	M1	MCB formwork & rebar assemble
G	Wall & inner formwork installation	M2	MCB concrete pouring & curing
H	Upper rebar assembling	-	-

The cost and duration of each activity are calculated from the site's daily work reports and labors' job log. Holidays and off-work days caused by weather conditions are excluded in calculating the durations. Also, direct costs for material and equipments are excluded from cost estimations because such expenses are not controlled by a site manager but by market prices. Moreover, since labor cost is the most risky in view of managerial aspect (Hanna *et al*., 2005); labor cost as the direct cost and indirect cost is calculated overall. Meanwhile, data fitting is performed from the collected cost and duration data, and several probability distributions are extracted for associated activities, such as exponential, uniform, normal, and beta.

4.3 Probabilistic Cost-Time Simulation and Alternatives

First, a 5,000-iteration of Monte Carlo simulation was performed using collected data and their fitted probability distributions. As opposed to common phenomena, it was found that there are no trade-offs between cost and time. This is presumably because that most labor resides at the site and gets paid for daytime work regardless of their actual inputs. In addition, overtime work accompanying the cost increase did not shorten the duration because most of the overtime work on this site occurred due to rework or catch-up on delays. Probabilistic distributions of final cost and time are shown in Figure 3. The mean values of total cost and duration are US$111.38 thousand and 30 days. When setting the target duration as 29 days on the right side of Figure 3, its estimated final cost on the left side was found to be US$110.00 thousand at 50% and US$118.67 thousand at 90% confidence level, respectively.

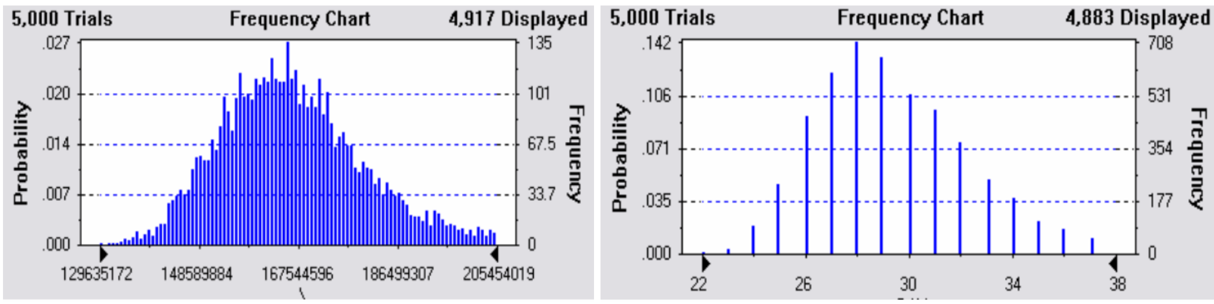


Figure 3: Historical Data-Based Simulation Results of Case Study Project

In addition, comparing to current probabilistic approach that applies normal distribution to every activity, it showed a 0.7% mean increase and a 22.3% standard deviation decrease in cost, and a 7% mean increase in duration. Moreover, it was found that there is a statistically significant difference between the results of proposed and current approach, through a T-test. Therefore, it is likely that the result of historical data-based approach could provide more accurate and meaningful information.

Next, a sensitivity analysis was performed to sort out activities to be improved. Table 2 shows each activity's contribution to cost and time variance, and probability that an activity will be on the critical pass. In this case study, the authors pointed out six activities for possible improvement that have over 4% contribution to variance and over 50% of probability to be on a critical pass. Then, through discussions with a site manager considering activity's feature and site conditions, activities A, F, H, and J were selected as they were expected to produce more impacts on productivity improvement.

Following the selection of activities, the authors considered possible application of simulation tools. Since discrete events in the activity F, H, and J are executed simultaneously without stable flows logically connecting predecessors and successors, we concluded that they are difficult to model through a discrete event simulation (DES). Therefore, a DES is applied to the activity A, while intuition of an experienced site manager is applied to the activity F, H, and J to draw valuable ideas for improvement with site investigations as well as labors' opinions.

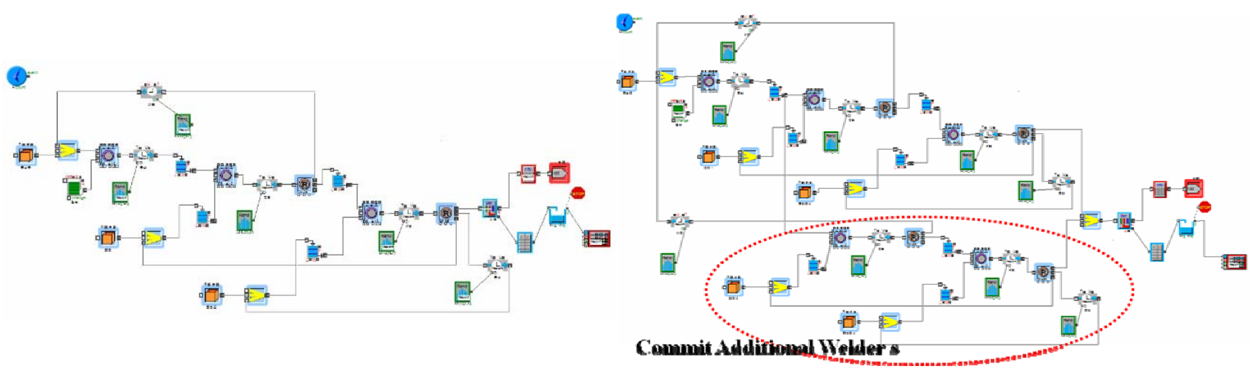
For developing DES model, activity A, floor and outer wall rebar assembling, was further divided into floor slab assembling, lower part rebar assembling, upper part rebar welding, and finishing. Among these operations, we focused on 'upper part rebar welding' since this element consists of a series of interconnected events within a cycle, including rebar transport, delivery to setting location, assembling, welding, and returning. From the productivity measurement using work sampling method and crew balance chart, it is found that there is comparatively a big idle time of two movers over the course of rebar transporting. Therefore, an alternative is suggested providing an additional welding crew sharing the movers. Figure 4(a) and 4(b) show the as-is and to-be process model. The simulation results showed that the 'to-be' process could reduce a cycle time, on average, by 20%.

Table 2: Result of Sensitivity Analysis

Activity	Sensitivity to Cost	Sensitivity to Duration	Enter into CP	Improved by
A	3.7%	4.0%	100%	DES**
B	1.4%	0.2%	100%	-
C	0.0%	0.0%	100%	-
D	0.0%	1.6%	100%	-
E	7.1%	9.6%	59%	-
F	9.2%	2.3%	59%	E.O.***
G	11.7%	7.5%	42%	-
H	7.1%	6.0%	59%	E.O.***
I	0.0%	0.0%	100%	-
J	42.7%	64.2%	100%	E.O.***
K	3.8%	4.6%	100%	-

* Dark cell represents higher ranked activities that require improvement.
** Discrete event simulation / *** Expert opinion.

Meanwhile, disposals of activities F, H, and J based on site conditions and a site manager's intuition are like following: (1) though upper rebar assembling (activity H) is a successive activity to diaphragm rebar assembling (activity F), there is a room for concurrent work because a cantilever rebar assembling in activity H is independent of activity F's completion, and (2) a strong wind and low temperature of the winter season had a bad influence on concrete curing (activity J), therefore, the duration could be shortened through installing additional heat-insulating materials with a bit of cost increase.



(a) As-is Process **(b) To-be Process**

Figure 4: Process Improvement of Activity A

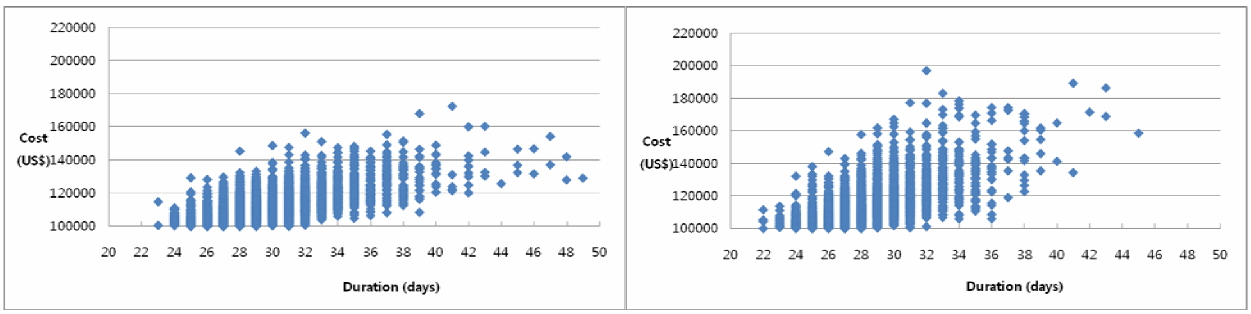
The last step in this case study is investigating possible combination of alternatives. Using activity A, F, H, and J, four options are devised and a Monte Carlo simulation is performed for each option. As shown in the Table 3, it is found that A-F-H and F-H option can cut down the expenses whereas others increase total cost. As well, all alternatives can contribute to shorten the total duration.

Table 3: Alternatives and Estimated Results

Alternative Options	Cost (Mean)	Cost (90% Confidence)	Duration (Mean)	Duration (90% Confidence)
None	US$111.39 thousand	US$124.03 thousand	30 days	34 days
A-F-H	US$110.99 thousand	US$123.90 thousand	29 days	33 days
A-F-H-J	US$111.43 thousand	US$127.92 thousand	28 days	31 days
F-H	US$111.09 thousand	US$123.66 thousand	29 days	33 days
F-H-J	US$111.50 thousand	US$127.47 thousand	28 days	32 days

It is also found that the alternative A-F-H-J is the most effective alternative in both cost and time perspectives. Comparing to current site situation (as-is state), the distribution of duration is narrowed within 44days through executing the option. However, there could be a cost increase as the duration shortens. The probabilistic distributions of each case's cost and time are shown in Figure 5.

Through the case study, it is demonstrated that the proposed framework can be effective in reflecting real construction site conditions and managing the uncertain cost-time in a practical and concurrent manner.



(a) As-is **(b) To-be**

Figure 5: Estimated Final Cost-Time Distribution

5. Conclusion

Cost and time control has long been an essential part of construction management, and many studies have used approaches ranging from deterministic approaches to probabilistic approaches. However, the current probabilistic approaches are deficient in ensuring practical probability distribution and establishing alternatives for process improvement in a reasonable and systematic way. This study suggested a practical decision-making procedure with the reality of the probabilistic approach based on historical data accrued from each activity's performance to close the gap in the current probabilistic approaches for cost-time analysis and scenario simulation. In addition, a framework for extracting alternatives to enhance current performance is also presented through productivity evaluation and discrete event simulation as well as the project manager's experiential intuition. This study also presented a detailed case study to demonstrate the practical applicability and the benefits of the proposed approach, and the results show how the proposed approach effectively improved statistically compared to traditional approaches in terms of cost and time. However, the application of the suggested framework in this study is limited to middle-phased projects that are composed of iterative processes and have enough past records to extract probability distribution. Moreover, since past records reflect characteristics of a specific construction site such as site manager and labors, use of probability distributions are also limited to the project. Therefore, future study is necessary on (1) estimating the cost and time probability distribution of a general construction project and (2) analyzing records with advanced tools that could get compensate for errors caused by site uncertainties such as accidents and weather conditions.

6. Acknowledgement

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