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Project cost–quality–risk tradeoff analysis in a time-constrained problem

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A R T I C L E I N F O

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A B S T R A C T

One of the main issues in any scheduling of projects is the difficulty of convincing customer on total project makespan. There are many occasions where customer informs the contractor that the schedule must be shortened. This action could lead to increase in total cost as well as risk, which may also end of having lower quality project. This paper proposes a multi objective mixed integer linear programming for minimizing "project total extra cost", "project total risk enhancement" and "project total quality reduction" subject to time constraint. In other words, the proposed study provides a tradeoff between the three mentioned objectives to shorten the overall project duration. Goal attainment method is used for solving the multi objective model and obtaining the Pareto-optimal solutions. The computational experiments are also applied to evaluate the efficiency of the proposed model.

1. Introduction

The classical Critical Path Method (CPM) has been applied as an acceptable technique for construction projects planning in the late 1950s (Kelley & Walker, 1959). CPM, in its original form, uses a forward pass analysis to detect the shortest total project duration according to both the duration of activities and the dependencies among them. The backward pass also completes CPM by detecting total floats and critical activities (Lu, Lam, & Dai, 2008).

After introducing CPM, many project scheduling methods have been developed and several network modeling formats have been used to represent the precedence of project activities. The CPM uses the activity-on node (AON) format to create a project network. In contrast, Arrow Diagramming Method (ADM) is a network diagramming technique in which activities are represented by arrows. ADM is also known as the activity-on-arrow (AOA) method. CPM and ADM only shows finish-to-start relationships, meaning that each activity must be completed before the successor activity can be started. Slight reflection reveals that precedence relations among activities need not be confined to the straitjacket of such strict precedence since other relations can, and do in fact; exist between activities (Elmaghraby & Kamburowski, 1992). Therefore, another method which is called the Precedence Diagramming Method (PDM) is developed in 1983 (Moder, Phillips, & Davis, 1983). The PDM is an extended version of the AON networks. It contains the capability to directly model start- to-start (SS), finish-to-finish (FF) and start-to-finish (SF) precedence relationships among activities as well as the strict finish-to-start (FS) relationship. These relationships are called Generalized Precedence Relations (GPRs) between a pair of activities. Moreover, the precedence diagramming method can also incorporate lead-lag factors into the relationships.

One of the important aims in project planning is to analyze the tradeoff among different components of the project characteristics. The time–cost tradeoff problem was introduced first (in comparison with other tradeoff problems) after the origination of the CPM, and is one of the more frequently discussed topics in the literature. Remarkable examples of project time–cost tradeoff problems are work of Fulkerson (1961), Berman (1964), Lamberson and Hocking (1970), Azaron, Katagiri, and Sakawa (2007), Ammar (2010), Hebert and Deckro (2011), Chen and Tsai (2011), Zamani (2013), Ke (2014), and Ke and Ma (2014). Fulkerson (1961) presented a linear programming problem of computing the least cost curve for a project composed of many individual tasks which has an associated crash completion time and normal completion time, and the cost of doing the tasks varies linearly between these extreme times. Berman (1964) described a conceptual model which allocates resources in a project network, the activities of

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which are subject to continuous concave-upward time–cost functions, in such a way as to achieve a minimum cost solution for a given completion date for the project. An algorithm based on convex programming is developed for optimum time compression in network scheduling systems by Lamberson and Hocking (1970). Their development allows for the activity time–cost tradeoff functions to be any differentiable convex function. Azaron et al. (2007) developed an analytical model for the time–cost tradeoff problem via optimal control theory in Markov networks. Ammar (2010) removed the assumption of constant value of activities' cost along the project time span and considered discounted cash flows for time–cost tradeoff optimization problem. A different approach for time–cost tradeoff analysis of a project network in fuzzy environments is proposed by Chen and Tsai (2011). Hebert and Deckro (2011) developed a linear programming model for reducing the primary project duration with respect to the cost minimization approach. Zamani (2013) developed an effective procedure for optimizing time–cost performance of multi-mode resource constrained project scheduling problems in which activities are subject to finish-to-start precedence constraints under renewable limited resources. Combined with uncertainty theory and dependent-chance programming, an uncertain random time–cost tradeoff model has been built by Ke (2014). The authors presented three types of time–cost tradeoff models, in which the project environment is described via introducing the fuzzy random theory in another work (Ke & Ma, 2014).

Recently, the tradeoff problems include other aspects in addition to time and cost. Babu and Suresh (1996) suggested that the project quality may be affected by project crashing and developed linear programming models to study the tradeoffs among time, cost, and quality. El-Rayes and Kandil (2005) presented a model for transforming the traditional two-dimensional time–cost tradeoff analysis to an advanced three-dimensional time–cost–quality tradeoff analysis. Tareghian and Taheri (2006) developed a solution procedure for the time–cost–quality problem with assumption of duration and quality of project activities to be discrete, non-increasing functions of a single non-renewable resource. Afshar, Kaveh, and Shoghli (2007) developed a metaheuristic multi-colony ant algorithm for the optimization of three objectives time–cost–quality as a tradeoff problem. Zhang and Xing (2010) presented a fuzzy-multi-objective particle swarm optimization to solve the time–cost–quality tradeoff problem. Salmasnia, Mokhtari, and Nakhai Kamal Abadi (2012) proposed a robust solution method to minimize the variation effect on time, cost, and quality. Kim, Kang, and Hwang (2012) used a mixed integer linear programming model which accounts for potential quality loss cost associated with rework or modifications that may occur due to excessive crashing activities. Tavana, Abtahi, and Khalili-Damghani (2014) considered a multi-objective multi-mode model for solving discrete time–cost–quality tradeoff problems with preemption and generalized precedence relations. Jeang (2015) adopted an approach that uses computer simulation and statistical analysis of uncertain activity time, activity cost, due date and project budget to address quality and the learning process with regard to project scheduling. Monghasemi, Nikoo, Fasaee, and Adamowski (2015) applied an evidential reasoning (ER) approach to identify the best Pareto solution for discrete time–cost–quality tradeoff problems. The tradeoff problems are not limited to time–cost or time–cost–quality. Xu, Zheng, Zeng, Wu, and Shen (2012) presented a discrete time–cost–environment tradeoff problem for large-scale construction systems with multiple modes under fuzzy uncertainty. Their objective functions are to minimize the total project cost, project duration, crashing cost, and environmental impact. Saputra and Latiffianti (2015) proposed a model to measure project reliability with time and cost as the targets by considering resource availability under uncertainty.

In this paper, one of the challenges faced by different projects in real situations is investigated. This challenge is explained as follows: The total project duration which has been scheduled by a contractor is not acceptable for the customer. A common technique used to shorten the overall project duration is to crash project activities. Crashing is modeled as a tradeoff between activity cost and duration in order to determine how the maximum crashing is achieved by the minimum cost increase. Crashing only notices to the tradeoff between cost and time but the time reduction of some activities leads to project threatening risk enhancement and project quality reduction which should not be neglected easily. It should be also noticed that any arbitrary activity cannot be chosen for its time reduction because this action can impose higher cost, more threatening risks and lower quality level of the project that make the customer unsatisfied or change the scope of the project. Therefore a solution should be sought to consider simultaneously cost, risk and quality of the project under the time constraint. The mentioned solution can be achieved by a mathematical programming and decision making technique. A multi objective model can be used for determining which activity should be shortened and how much they should be reduced in order to impose the minimum cost, risk and quality degradation on the project. Hebert and Deckro (2011) investigated a similar study but they only paid attention to the project cost and time and neglected the other significant project elements such as risk enhancement and quality reduction which are created by reducing completion time of a given project activity. Since the completion time reduction of activities increases risk and decreases the quality needed for completing the activities (leads to quality reduction of the overall project), the mentioned elements should not be easily overlooked.

For solving the proposed model, we first transform the multi objective model into an equivalent single-objective problem by using the goal attainment technique. Goal attainment is introduced by Gembicki and Haimes (1975) and then was applied for using a number of real world multi-objective problems in various fields (Azaron, Brown, Tarim, & Modarres, 2008; Azaron, Katagiri, Kato, & Sakawa, 2006a; Azaron, Katagiri, Kato, & Sakawa, 2006b). Goal attainment technique is one of the multi objectives techniques deals with decision maker's preference information which should be obtained before solving a model. The optimal solution obtained by this technique is the Pareto-optimal solutions which are extremely sensitive to both goal and weight vectors that are elicited by decision maker. Requiring fewer variables than interactive techniques and solving fast the model in one stage are considered as the advantages of goal attainment method in comparison with other multi-objective techniques.

We deal with a mixed integer linear programming (MIP) after transforming the multi objective model into an equivalent single-objective one. The transformed model is solved using the software LINGO 11.0 (Schrage, 1998) which is an optimization software commonly used to solve mixed integer linear programming problems. It implements Branch & Bound methods for global optimization. LINGO's implemented algorithm leads to an exact solution for MIP problems (D'Ambrosio & Lodi, 2011).

Vavasis (1991) proved that MIP problems belong to the class of NP-complete problems. In other words, the MIP problem cannot be solved within a polynomial time. Since, LINGO comes with a model size limitation of 3000 variables and 2000 constraints (D'Ambrosio