Contents lists available at SciVerse ScienceDirect

Engineering Applications of Artificial Intelligence

journal homepage: www.elsevier.com/locate/engappai

A fuzzy clustering-based genetic algorithm approach for time–cost–quality trade-off problems: A case study of highway construction project

Santosh Mungle [a], Lyes Benyoucef [b,*], Young-Jun Son [a], M.K. Tiwari [c]

[a] Department of Systems and Industrial Engineering, University of Arizona, AZ 85721-0020, USA
[b] Aix-Marseille University, LSIS, CNRS-UMR 7296, Avenue Escadrille Normandie Niémen, 13397 Marseille Cedex 20, France
[c] Department of Industrial Engineering & Management, IIT Kharagpur, 721302 India

ARTICLE INFO

Article history:
Received 19 September 2012
Received in revised form
2 May 2013
Accepted 10 May 2013

Keywords:
Time–cost–quality trade-off
Multi-objective optimization
Fuzzy clustering
Project management

ABSTRACT

Recently government agencies have started to utilize innovative contracting methods that provide incentives for improving construction quality. These emerging contracting methods place an enormous pressure on the contractors to improve construction quality. For a general contractor, which subcontracts most tasks of a project and invites a number of bids, choosing an appropriate bid which satisfies the time, cost and quality of construction project is complex and challenging. To solve this problem involving conflicting objectives, a fuzzy clustering-based genetic algorithm (FCGA) approach is proposed in this paper. A case study of highway construction is used to demonstrate the applicability of the proposed approach. A comparative study is conducted over three test cases involving varying dimensions and complexities to test performance of the proposed FCGA against existing approaches. Results reveal that the FCGA is capable of generating better Pareto front than other existing approaches.

1. Introduction

Transportation agencies have been implementing various contracting methods for highway construction, such as (1) bidding on cost/time (*i.e.*, A+B method) that encourages contractors to minimize project duration (Herbsman, 1995); (2) multi-parameter contract that provides incentives to the contractors for improving quality performance (Anderson and Russell, 2001); (3) incentive/disincentive contract that provides contractors with financial support to reduce a project completion time (Jaraiedi et al., 1995); and (4) warranties contract that attempts to improve construction quality by making contractors liable for the performance of the facility after project completion (Anderson and Russell, 2001). These contracting methods place an increasing pressure on the main contractors to improve their project performance. While many contractors invited bids for subcontracting activities based on time–cost trade-off only previously, they need to incorporate quality together with time–cost trade-off nowadays when subcontracting the activities due to the immense pressure on improving the performance quality by government agencies such as Department of Transportation. It is quite tedious and complex to decide which bid/subcontracting alternative to be accepted in planning and scheduling of the entire project, and to simultaneously satisfy the project requirements such as project time, cost and quality due to its conflicting nature.

1.1. Context

According to the Project Management Institute (PMI, 2001), quality must address both the management of the project as well as the project result. More specifically, PMI (2001) states that “*The cost and schedule adjustment may require meeting the specified quality standard and it implies that there is trade-off across cost, schedule and quality*”. However, the conventional project management trade-off between time and cost is originally known as a time–cost trade-off problem. It means that the amount of time required to finish an activity depends on how much cost is paid by the project planner. To finish the activity with less time requires more or higher quality resources at a higher cost. Time–cost trade-off problem is known as a NP-hard problem which has failed to maintain pseudo-polynomial time guarantee for complex project networks using exact solution algorithms (De et al., 1997). Therefore, researchers have proposed meta-heuristics such as genetic algorithm (GA), ant colony optimization (ACO) and simulated annealing (SA) to solve the time–cost trade-off problem within a reasonable time (Feng et al., 1997, 2000; Zheng et al., 2005; Chassiakos and Sakellaropoulos, 2005; Ozgen, 2009; Zhang and Li., 2010; Pour et al., 2010; Xu, 2011; Mokhtari et al., 2011; Zhang and Ng., 2012).

On the other hand, a few problem formulations have been proposed by researchers for time–cost–quality trade-off problem

* Corresponding author. Tel.: +33 677576400.
E-mail addresses: lyes.benyoucef@lsis.org, lyes.benyoucef@univ-amu.fr (L. Benyoucef).

0952-1976/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.engappai.2013.05.006

using mix integer programming. Mostly they adapted meta-heuristics such as multi-objective genetic algorithm (MOGA), multi-objective ant colony optimization (MOACO), multi-objective particle swarm optimization (MOPSO), and electromagnetic scatter search (ESS) to handle the computational intractability of the proposed and adapted mathematical formulations (Rayes and Kandil, 2005; Tareghian and Taheri, 2007; Afshar et al., 2007; Rahimi and Iranmanesh, 2008; Pour et al., 2012; Sonmez and Bettemir, 2012).

1.2. Motivations

A major task in early project planning is to identify and allocate the major activities of a large project to several subcontractors for its completion. Pells (1993) pointed that "*the selection of subcontractor is a rigorous, difficult and time-consuming process*". The selection of optimal subcontracting options depends on topology of the project network and the extent of the project owner information relative to the available pool of subcontractors for each activity (Gutierrez and Paul, 2000). Prior to execution, project owners have very limited information about the true cost and duration of a project because inevitably it depends on the capabilities of the subcontractors performing the activities. Gutierrez and Paul (2000) showed that "*the problem of designing the contract mechanism to allocate the activities of the large project to one or several subcontractors for execution has important implication for project success*". For validation, they consider two real life projects: (1) laying out a belt of highway from one point to another and (2) construction of a gas distribution network in a city. Their results showed that the project duration can be reduced significantly by successful implementation of a subcontracting mechanism for large construction projects. Recently, implementation of new contracting methods by government agencies such as Department of Transportation increases pressure on the project owners for improving the performance quality. *This motivates the decision makers in construction industry to incorporate quality with time–cost trade-off while subcontracting the project activities*.

Later, Johnson and Liberatore (2006) proposed a formulation for time–cost–quality trade-off by incorporating quality into traditional time–cost trade-off. The main idea was to improve a project performance via subcontracting the project activities. They validated the proposed formulation on a small scale hypothetical example. They suggested that successful implementation of a subcontracting mechanism may improve the project performance viz. project time, cost and quality significantly. However, their formulation is not based on the multi-objective one. Instead, it only maximizes project quality while project cost and duration are used as constraints. Moreover, it does not consider incentive and penalty cost provided to the contractor based on their project performance in determining the project cost while they are commonly used by construction industry (Bubshait, 2003).

Nevertheless, real life construction projects involve larger number of activities with a more complex network structure. For example, if we have 20 activities in the project and each activity has 4 subcontracting alternatives, it creates 1.1 trillion (*i.e.*,4^{20}) possible combinations to schedule the entire project. To select the optimal subcontracting option for each activity which satisfies all the objectives viz. project time, cost and quality with imposed constraints by transportation agencies from such a huge solutions space is computationally intractable. Moreover, a Pareto set for such a multi-objective problem with three conflicting objectives can be extremely large and may even contain infinite number of solutions (Morse, 1980). Therefore, reducing the size of the Pareto set without destroying its characteristic is desirable from a decision maker's perspective. This has motivated the authors to propose a novel approach to solve computationally complex time–cost–quality trade-off problems for large highway construction projects.

1.3. Contributions and outline of the paper

This paper formulates a multi-objective mathematical model for time–cost–quality trade-off problem, which involves a number of equality and inequality constraints. Moreover, incentive and penalty cost are explicitly considered in the formulation to determine the project cost. The proposed mathematical model is believed to mimic the practical time–cost–quality trade-off problem in the construction industry. Quality measurement approach is presented using analytic hierarchy process (AHP) technique to evaluate an anticipated quality of the proposed work by subcontractors for each activity in the project. Finally, a novel approach called fuzzy clustering-based genetic algorithm (FCGA) is developed to solve the time–cost–quality trade-off problem.

The skeleton of the proposed FCGA approach encompasses various established multi-objective techniques, ingeniously modified, to make the overall approach competitive and compatible with the problem at hand. The proposed approach incorporates fuzzy clustering technique with non-dominated sorting genetic algorithm (NSGA-II) to provide representative and manageable Pareto set. Moreover, the FCGA uses an external repository concept to preserve non-dominated solutions found along the search process. The fuzzy clustering technique manages the size of repository within limits without destroying the true characteristics of the Pareto front. In addition, FCGA uses a fuzzy membership function to determine the best compromise solution.

To validate the efficacy and applicability of the proposed FCGA, a case study of highway construction industry is included. The comparative study has been conducted on the three test cases to demonstrate a superiority of the proposed approach. Moreover, the performance analysis has been conducted to investigate the performance of the proposed approach on the three test cases against those of other multi-objective optimization approaches.

The rest of the paper is organized as follows. Section 2 deals with the problem formulation. Section 3 presents a quality measurement approach for construction activity. Section 4 describes the terminology in multi-objective optimization. Section 5 provides the detailed discussion of the proposed FCGA algorithm. Section 6 discusses the implementation methodology of the proposed approach on the multi-objective highway construction problem. Section 7 shows an experimental study on the case study of highway construction industry. Section 8 provides the comparative study and the performance analysis of the proposed approach with existing methods. Finally, Section 9 concludes the paper with suggested future work.

2. Problem description and formulation

The time–cost–quality trade-off problem in highway construction can be described as follows: Consider a general contractor to start planning of a highway construction project. The project consists of total N activities. Due to precedence relationships among those activities, project forms an activity network. Usually, contractors are not able to complete the whole projects by their own capacity and resources. Therefore, they put each of the various activities individually up for bids, and receive bids with both duration and cost from different subcontractors. For each time and cost option, contractors apply the AHP based on the information that they have about the subcontractor to evaluate the anticipated quality of the activity.

For reader's convenience, Table 1 summarizes mathematical notations used in the proposed formulation in this paper.