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Gas and oil project time-cost-quality tradeoff: Integrated stochastic and fuzzy multi-objective optimization applying a memetic, nondominated, sorting algorithm

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ABSTRACT

Stochastic time-cost-quality tradeoff problem (STCQTP) analysis significantly expands the scope of discrete (deterministic) project duration-cost analysis. STCQTP requires multi-objective optimization methodologies to locate optimum total-project-cost-quality solutions for facilities-construction projects with multiple parallel pathways of work items involving high degrees of duration, cost and quality uncertainties; a situation common in the gas and oil industry. Calculating Pareto frontiers of non-dominated-total-project-cost and total-project-quality solutions across the range of feasible project durations further extends the usefulness of STCQTP analysis. For stochastic analysis project-work-item durations and costs are expressed as probability distributions and sampled with random numbers (0,1). By controlling the fractional numbers used to sample the work-item cost distributions by formulas linked to the random numbers used to sample the work-item duration distribution, a wide range of complex time-cost relationships can be defined. Fuzzy analysis is applied to each stochastic case generated to integrate more subjective assessments of work-item quality achieved. A memetic algorithm, developed for constrained STCQTP involves ten metaheuristics configured to combine local exploitation and global exploration of the feasible duration-cost solution space. Fuzzy analysis of work-item quality is integrated with each stochastic scenario evaluated. The proposed algorithm effectively delivers realistic multiple objectives of: 1) global total-project-cost minima; 2) global total-project-quality minima; and, 3) Pareto frontiers of non-dominated total-project duration versus cost, duration versus quality, and/or duration versus total-project-cost-quality function test score. Analysis of an example gas-processing-plant-construction project, applying three distinct work-item duration-cost relationships, demonstrates with the aid of metaheuristic profiling, that the memetic STCQTP algorithm coded in visual basic for applications for execution via an Excel spreadsheet, requires no proprietary software to deliver its objectives. Dynamic adjustment factors applied by some metaheuristics, derived from fat-tailed distributions sampled by chaotic sequences, aid efficient searching of the feasible solution space. The metaheuristic profiles also help to fine tune the metaheuristic configurations of the algorithm applied to specific project cases.

1. Introduction

The gas and oil industries frequently run into problems failing to meet budgeted-facilities-construction project cost, schedule and quality. Wood (2017) highlighted some high-profile gas and oil industry projects suffering spectacular budget and schedule overruns and quality failings in recent years. Conducting sufficient analysis and multi-objective optimization of projects' time-cost-quality tradeoffs are therefore an essential requirement in the effective planning of all gas and oil industry construction projects of any size. Such analysis is also crucial for many other industries and types of project, and it needs to be performed while satisfying several constraints (e.g., project network and critical path logic, work-item precedence, resource availability, contractual terms, budget limits, quality standards etc.). This multi-objective, highly-constrained challenge needs to identify a schedule that can deliver a project at the lowest total-project cost while satisfying all the constraints, while delivering it at optimum, or at least acceptable,

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quality standards. Zhou et al. (2013) review techniques typically used to optimize scheduling in construction projects; but focusing on schedule only addresses part of a multi-dimensional challenges.

Discrete (deterministic) time-cost-tradeoff problems (DTCTP) for construction projects are widely researched and applied (e.g., Bettemir and Birgonul, 2016). The scenarios considered typically assume very specific relationships between cost and duration of project's component work items, viz., work-item duration can be reduced by incurring additional expenditures to undertake "crash" actions. Such actions lead to the direct project-cost (material, labor) of the work item increasing, whereas the indirect cost (overheads) of the activity decreases, because less days of oversight are required. DTCTP typically evaluate a few multi-modal cases, i.e., deterministic work-item duration and cost estimates for several alternative construction techniques available for potential selection, based upon quotes provided by different sub-contractors. One problem is that at the early stages of a project detailed quotes on highly specified work-item requirements are not available; so, the estimates used for deterministic cases are subject to high degrees of uncertainty.

Although the multi-modal DTCTP is a common scenario considered in gas-and-oil project planning. It is typically a precursor to a final-investment decision to sanction a project and award of engineering, procurement and construction (EPC) contracts to the "optimum" (deterministically-defined) design. However, DTCTP is not the only scenario that could be used for project planning. The uncertainties that exist in early project planning stages justify the application of more-expansive evaluations of stochastic time-cost-quality tradeoff problems (STCQTP). STCQTP involve continuous distributions, expressed as probability distributions, for the duration and costs of each work item. Even at later stages of project development, significant uncertainty remains concerning the durations of contracted work items during project implementation. This is due to factors such as contractor performance, variations between quality achieved and planned specifications, inflation of materials costs, weather, unplanned interruptions and change orders. Performing STCQTP during project *implementation* stages can also be more beneficial and realistic than DTCQTP analysis. At the implementation stage this would involve applying narrower distribution ranges for duration and cost and less vague duration-quality relationships, than would be applied in early-stage project-planning analysis.

Such uncertainties expose the limitations of discrete project optimization models and justify the application of stochastic project evaluation and review techniques (PERT) that incorporate quality consideration into critical path method (CPM) analysis. This study describes a STCQTP approach for early-stage and implementation-stage project planning that minimizes project costs. It optimizes work-item quality across a range of feasible total-project durations (makespans) for different probabilistic activity time-cost relationships. It applies a recently-developed memetic, nondominated, sorting optimization algorithm that monitors performance of the component metaheuristics of that algorithm with the recently-developed technique of metaheuristic profiling (Wood, 2016a,b).

2. Evolution of project duration-cost-quality optimization techniques

Fulkerson (1961) and Kelley (1961) applied CPM model project schedules to identify designs associated with minimum total-project costs. More-complex relationships between project work item durations and costs were considered (Siemens, 1971; Reda and Carr, 1989) together with the risks associated with each metric (Wollmer, 1985; Moselhi and Deb, 1993). The ability to "crash" certain critical work items by incurring additional direct costs, constrained by available resources is widely applied (Ahn and Erenguc, 1998; Gutjahr et al., 2000). The DTCTP (Harvey and Patterson,1979; Hindelang and Muth, 1979) has evolved such that durations of each work item are typically defined, in several alternative modes, as discrete, non-increasing functions of the amount of non-renewable resource dedicated to each work item (Wuliang and Chengen, 2009). DTCTP is the focus of many construction-related optimization studies (e.g., De et al., 1995; Zheng, 2015; Aminbakhsh and Sonmez, 2016), posing an NP-hard optimization problem, and becoming more so as additional optimization objectives are factored in (Van Peteghem and Vanhoucke, 2010; Singh and Ernst, 2011; Zhang et al., 2015). The feasible solution space of a DTCTP increases exponentially as the number of project activities increases (Tavana et al., 2014). In cases where multiple objectives are sought (e.g., cost, time, quality etc.) the Pareto frontier (or front) can provide nondominated cost-quality solutions associated with a range of feasible total-project durations (Chau et al., 1997; Feng et al., 1997; Zheng et al., 2005; Vanhoucke and Debels, 2007; Iranmanesh et al., 2008; Gomes et al., 2014; Koo et al., 2015).

Project quality achieved is impacted by time-cost tradeoffs and, therefore, the time-cost-quality tradeoff is better considered as a complex continuum to be optimized (Babu and Suresh, 1996). Many attempts exist to treat project time-cost-quality optimization as a discrete tradeoff problem (DTCQTP) with each work item defined deterministically in several modes (Khang and Myint, 1999; El-Rayes and Kandil, 2005; Tareghian and Taheri, 2006; Kim et al., 2012). Some models incorporate fuzzy logic to address the difficult-to-quantify uncertainties associated with project quality and resource utilization (Zheng and Ng, 2005; Ahari and Niaki., 2013; Mungle et al., 2013; Shahsavari Pour et al., 2012; Zahraie and Tavakolan, 2009; Zhang and Xing, 2010). Others apply multi-criteria decision-making techniques, such as Analysis Hierarchy Method (AHP) (Pollack-Johnson and Liberatore, 2006) or evidential reasoning (Monghasemi et al., 2015) to assess project quality. Ke (2014) applies uncertainty theory to address non-random and non-fuzzy uncertainties in TCTP. A strong case can be made that the DCTCP is too-narrowly specified to cover many of the real project uncertainties encountered (Vahidi, 2013), which is the position taken in this study. In large projects, such as many gas and oil industry facilities projects, which take several years to construct, it can sometimes be appropriate to focusing on maximizing profitability rather than minimizing project costs. One way to achieve this is to optimize costs adjusted for time-value discount factors rather than to minimize undiscounted costs (Zareei et al., 2014).

Methodologies applied to optimize TCTP are classified (Zhang and Xing, 2010) into heuristic methods (Fondahl, 1961; Siemens, 1971; Moselhi, 1993; Elazouni, 2009), mathematical methods (Robinson, 1975; Elmaghraby, 1995; De et al., 1995; Burns et al., 1996) including branch-and-bound methods (Rostami et al., 2014), and metaheuristic models (Feng et al., 1997; Li and Love, 1997; Zheng et al., 2004; Elbeltagi et al., 2005; Hegazy, 2011), with further examples of each listed by Zhou et al. (2013). Heuristics are approximate rules-of-thumb, developed using problem-specific information, and tend to easily get trapped at local optima. On the other hand, metaheuristics are computational methods that optimize by iteratively trying to improve a candidate solution regarding a given metric(s) (Suh et al., 2011). The metaheuristic models applied to TCTP are typically, but not exclusively, evolutionary in nature, dominated by genetic algorithms (Chau et al., 1997; Sonmez and Bettemir, 2012). Evolutionary algorithms applied to DTCTP also including ant colony (Ng and Zhang, 2008), particle swarm (Rahimi and Iranmanesh, 2008), differential evolution, simulated annealing (Rasmy et al., 2008; Anagnostopoulos and Kotsikas, 2010), harmony search (Geem, 2010), frog leaping