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Metaheuristics for multi-mode cash flow balanced project scheduling with stochastic duration of activities

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ABSTRACT

This study investigates the multi-mode cash flow balanced project scheduling problem with stochastic duration of activities. The objective is to generate a robust baseline schedule to minimize the contractor's maximal cumulative gap between cash outflows and cash inflows. Owing to the NP-hardness of the problem, we develop two metaheuristics, i.e. simulated annealing (SA) and tabu search (TS), which have different search structures and are equipped with an improvement measure, to solve the problem. An extensive computational experiment is conducted on a data set generated by ProGen to evaluate the performance of the metaheuristics. The results demonstrate the effects of the improvement measure and indicate that the efficiency of TS decreases, whereas that of SA tends to increase with increasing problem scale. The influence of the key parameters on the objective function is analyzed and the following conclusions are drawn: The contractor's maximal gap of cumulative cash flows decreases with an increase in the expected project deadline, times of attenuation coefficient, payment number, compensation proportion, advanced payment proportion, whereas it increases with an increase in the times of marginal cost and the retention proportion.

1. Introduction

With the rapid development of the global economy, the scale of certain important projects is becoming increasingly larger, which causes the project investment to increase considerably. Moreover, if the contractor's financing ability is limited, the project may fail owing to activities that cannot be fulfilled without adequate capital. In this circumstance, a capital chain rupture, which is a concept in business finance management that always results in business failure, would be incurred. To prevent this circumstance, contractors must offset their cash outflows for labor, equipment, materials, and so on, with the client payments, which are considered the contractors' cash inflows during project execution. Therefore, it is highly important for contractors to maintain the balance between their own cash outflows and cash inflows during the execution of projects to guarantee the smooth completion of projects with poor financing. However, because there are numerous uncertain factors in projects, it is difficult to maintain the cash flow balance throughout the project. First, uncertain factors may change the completion times of activities and hence influence the times of occurrence of cash outflows and cash inflows. Second, uncertain factors may have a direct effect on the amounts of cash outflows and cash inflows because contractors incur additional expenses to tackle problems caused by these uncertain factors. Moreover, uncertain events may result in the adjustment of payment amounts from the client. For the aforementioned reasons, the method of balancing contractors' cash outflows and cash inflows during project execution processes is undoubtedly a meaningful problem. This is designated the cash flow balanced project scheduling problem (CFBPSP) and it must be studied intensely, especially in an uncertain environment. In this paper, we address the multi-mode version of CFBPSP, i.e., MCFBPSP, with stochastic duration of activities. This is because, in practice, contractors typically choose different activity modes for cash flow adjustments.

The project scheduling problem of balancing, controlling, and optimizing the project cash flow has been addressed since approximately 2004 and has been referred to as "finance-based scheduling." Elazouni and Gab-Allah [1] introduced an integer-programming finance-based scheduling method for construction projects to produce financially feasible schedules that balance the financing requirements of activities over any period. Alghazi et al. [2] introduced a shuffled frog-leaping algorithm (SFLA) to solve finance-based scheduling problems and demonstrated that SFLA improved the quality of solutions with a substantial reduction in computational time. Alghazi et al. [3] proposed an improved algorithm to solve the same problem by introducing a repair algorithm for the finance-infeasible chromosomes generated within a genetic algorithm (GA), and the repaired-chromosome GA is proven to be superior in terms of computational cost and the quality of solutions.

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Elazouni et al. [4] compared the performance of a genetic algorithm (GA), simulated annealing (SA), and a shuffled frog-leaping algorithm in solving the discrete versus continuous variable optimization problems of finance-based scheduling. It must be noted that cash flows are only treated as a type of resource constraint and the objective remains to minimize the makespan in these finance-based scheduling problems. However, the aim of CFBPSP is to assist the contractor in minimizing his/her maximal cash flow gap during the project execution process. It is clear that research on the finance-based scheduling problem can lead to a minimal makespan schedule where the capital constraint is feasible, whereas the research on CFBPSP can determine the minimum financing ability for the contractor. It is beneficial for the contractor to make decisions from a number of options.

In addition to the aforementioned finance-based scheduling, another important research branch is project scheduling with the cash availability objective, which has attracted the attention of some researchers. The notion of cash availability as a means for evaluating projects is presented and discussed by Goldratt [5]; according to Demeulemeester and Herroelen [6], this objective is a non-regular measure of performance that is not a non-decreasing function of the activity completion time. In view of the fact that cash availability in projects is analogous to work-in-progress inventory costs during production, Szmerekovsky and Vairaktarakis [7] considered the project scheduling problem of maximizing the cash availability of a project by solving its equivalent problem, i.e., minimizing total weighted flowtime. They describe the structure of an optimal solution and provide several efficient algorithms and their complexity based on mincost and maxflow formulations. Gutjahr [8] surveyed models for project portfolio selection; these models incorporate the development of skills by learning and/or forgetting. The author shows how these models, which assist in making a tradeoff between immediate financial returns and strategic benefits, are used as components of approaches to support staffing and scheduling decision.

With regard to the project scheduling problem with cash flows, most researchers focus on Max-NPV PSP, which was first presented by Russell [9], whereas a minority of scholars treats the cash flow as a type of constraint, i.e., the capital constrained project scheduling problem (C-CPSP). Doersch and Patterson [10] proposed and defined a new CCPSP, where capital is seen as a nonrenewable resource, and formulated the associated binary integer program. Smith-Daniels and Smith-Daniels [11] discuss the effect of capital and material costs in an integrated fashion in the project scheduling problem where the net present value of a project is maximized. Assuming that capital is a renewable resource, Smith-Daniels et al. [12] advance to study a relatively large CCPSP and present three heuristics for solving it. With the constraint of renewable resources, Icmeli and Erengüc [13] introduced a new model of the discrete time/cost tradeoff problem, where the objective is to determine the timing and durations of activities to maximize the NPV of all cash flows. Liu and Wang [14] established a resource-constrained project scheduling model with cash flows, and maximized the net project cash flow to optimize project profit from the perspective of contractors. In contrast to the studies above, where activities are assumed to be performed with a single mode, Mika et al. [15] considered the general multi-mode Max-NPV PSP, where a positive cash flow is associated with each activity, and proposed SA and TS to solve it. Given the fact that the amount and timing of progress payments are unknown, Kavlak et al. [16] formulated a payment project scheduling problem (PPSP), where the amount and timing of progress payments are important variables in the context of a multi-mode resource-constrained project scheduling problem with discounted cash flows. Furthermore, He et al. [17] defined a novel problem that designated the capital constrained project payment scheduling problem as the combination of a CCPSP and the PPSP, where the capital constraint is a renewable resource because of the supplemented progress payments of the client.

Note that all studies described above were established in a deterministic environment. To date, there are few authors committed to researching Max-NPV PSP in a stochastic environment. The early contribution to the research is from Buss and Rosenblatt [18], who assumed that activity durations are distributed exponentially with a known mean and they developed optimal and approximate procedures to determine the amount of delay of the various activities. Benati [19] engaged in determining a feasible activity schedule to maximize the net-present-value (NPV) of the project cash flow where the completion times of activities are random. Sobel et al. [20] present an algorithm to identify an optimal adaptive policy to schedule a project where the objective is to maximize the expected present value of the project cash flow and the activity duration is stochastic. In contrast to the uncertainty of activity durations in the assumptions above, Creemers et al. [21] examined project scheduling with the NPV objective where the project may fail if any activity is not performed. Furthermore, Wiesemann et al. [22] present a formulation that maximizes the NPV of a project when the activity durations and cash flows are described by a discrete set of alternative scenarios with associated occurrence probabilities. Zhang and Elmaghraby [23] investigated the effect of cost progress on financial risks during the execution of a project under uncertainty through Monte Carlo simulations. We refer readers to references [24,25], which summarize previous related works regarding Max-NPV PSP.

Proactive scheduling is a typical method of addressing uncertainty in a scheduling environment. It incorporates uncertain information to generate a robust pre-schedule that is protected as much as possible against disruptions during schedule execution. In an earlier effort, Goldratt [5] introduced critical chain/buffer management (CC/BM) to the field of project scheduling; this is based on the theory of constraints and defines three types of buffers to absorb delays. Herroelen and Leus [26] highlighted its merits of providing a new management mechanism, and also noted its pitfalls. Its focus is limited to the optimization of the global objective, ignoring the stability of the activity starting time, which may result in disturbances to schedules. Therefore, there are a few studies on robust scheduling in which the deviation of the activity starting time is minimal. Herroelen and Leus [27] developed and evaluate various approaches for constructing a stable pre-schedule where only one activity duration disruption is expected to occur during project execution. In a multi-disruption project, Leus and Herroelen [28] proposed a model for resource allocation for projects with variable activity durations, and this allocation is required to be compatible with a deterministic preschedule. In addition, Van de Vonder et al. [29,30] investigated the trade-off between project makespan performance and stability by adding concentrated safety time and inserting scattered time buffers for the schedule without and with resource constraints, respectively. The results inspire project managers to choose the proper buffering strategy based on the characteristics of the project to be scheduled. More comprehensively, Van de Vonder et al. [31] proposed multiple heuristic procedures including heuristic and metaheuristic algorithms, to allocate time buffers to the given schedule. The authors found that starting time criticality (STC) ranks best among these heuristics because it uses information on both activity weight and duration variability for a buffer allocation process. Furthermore, Deblaere et al. [32] proposed a stochastic methodology based on the newsvendor problem for the determination of a project execution policy with the objective of minimizing the cost function for the general RCPSP, and then demonstrated its effectiveness. In contrast to the activity duration uncertainty, the problem of uncertainty with respect to resource availability has been addressed by Lambrechts et al. [33,34]. The former aims at generating a stable baseline schedule and presents a TS procedure that operates on the free slack-based objective function. The latter determined analytically the impact of unexpected resource breakdowns on activity durations and used this information to develop an approach for inserting explicit idle time to generate a stable baseline schedule. We refer readers to a survey paper [35] that summarizes in detail other studies in the field of proactive scheduling.

Based on this literature review, we insert time buffers for activities