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Project scheduling for minimizing temporary availability cost of rental resources and tardiness penalty of activities

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ABSTRACT

This paper addresses the resource availability cost problem with rental resources where each activity has a given due date to be completed. In this problem setting, the required resources are temporarily rented to accomplish the corresponding activities where the paid fee for the rental resources depends on duration of their availability. In addition, each activity would be subjected to a tardiness penalty if its finish time surpasses its given due date. A mathematical model is presented for the problem and some features of its solution space are established. Also, a best-performed version of ant colony optimization (ACO) algorithm based on Ant Colony System is developed to tackle this strongly NP-Hard problem. The proposed method consists a new compatible schedule generation scheme, a new resource based heuristic role and an efficient local search. In a comprehensive experimental effort, the proposed parameters-tuned approach is compared with the exact solutions obtained by GAMS on several small-scale instances, while results of a competitive metaheuristic based on Genetic Algorithm are employed to validate the developed ACO algorithm for the large-scale instances. Finally, effectiveness of the proposed ACO is analyzed using statistical tests and the impact of the crucial parameters on the resulting solutions is demonstrated.

1. Introduction

The resource constrained project scheduling problem (RCPSP) has been widely studied in the literature [1]. Minimizing duration of project has been the most popular objective function in the literature of project scheduling. Recently, financial objectives have gained special attention by many researchers mainly because cost overruns have been one of the most crucial causes of projects' failure. Resource scarceness is a fundamental issue which project managers encounter with that in almost all construction projects. This has led to a wide range of related research works trying to help the mangers to make a satisfying decision [2–4].

The resource availability cost problem (RACP) is one of the close relatives of RCPSP which is strongly NP-Hard [5]. The RACP involves determining availability levels of the resources and scheduling the project's activities for minimizing the total cost of resources subject to a set of precedence relations, resource constraints and a deadline for project's makespan. In the RACP, all determined levels of the resources are being bought at outset of the project independent of their usage. Different versions of the RACP are studied in the literature to cover a broad range of its applications in various areas such as project scheduling [6–9], software engineering [10], and military capability planning [10–12].

Although the fixed availability of the resources may be acceptable for many resource types such as ordinary workers, light tools and low-price instruments, but it is not the case for heavy equipment like cranes, trucks and professionally skilled human resources like lawyers and consultants. Resource renting problem (RRP) introduced by Nübel [13] is a realistic version of the RACP which its objective is minimizing the total procurement cost of the bought resources and renting cost of the rented resources. Typically, the procurement costs are independent from their length of usage while the renting costs are a function of duration of their availability. In the existing literature, Ballestín developed a genetic algorithm with different codifications and metaheuristic algorithms to solve the RRP considering time-lags between project's activities [14,15]. Recently, Vandenheede extended the RRP by combining the classic resource renting problem and total adjustment cost problem. They developed a scatter search method to solve the problem which consists a novel heuristic [16].

It is remarkable that trying for minimizing makespan of a project predominantly contrasts with minimization of the project's costs. Therefore, developing an integrated model considering both criteria would be beneficial for project managers to have a real-life

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scheduling and renting policy. To the best of our knowledge, there is no previous work in the literature considering an integration of the resource renting problem and project scheduling problem for minimizing the tardiness penalty cost which is a challenging problem especially in just-in-time (JIT) environments.

As the main contribution of this paper, we present a novel version of the RACP supposing a deterministic due date for each activity to deal with especial requirements of a JIT environment. This is the case for many projects which contractor has been obliged to the client for delivering any activity of the project in a predetermined date. In order to homogenize both criteria, we consider tardiness penalty for each time unit of violation from the given due dates. In contrast with the classic RACP which assumes availability of all resources throughout the project's length with a fixed cost, we assume that the rental resources are temporarily available in a portion of the project's planning horizon with a cost structure which depends on availability length of the resource. We call this new version of the problem as RRP with tardiness (RRPT). The classic RACP can be interpreted as a special case of RRPT which in all the renewable resources are available throughout the project's horizon and tardiness penalties for all the activities and availability cost of all the resources are zero. Also, the classic RRP is included in the RRPT by setting the tardiness penalties for all the activities to be zero. As the second contribution, we develop a calibrated ant colony system (ACS) metaheuristic algorithm to solve the RRPT. In the proposed algorithm, we apply an important characteristic of the RRPT's solution space for constructing the solutions. Finally, as the last contribution, we evaluate performance of the developed algorithm based on several benchmark test instances. In doing so, the results obtained by the proposed ACO are compared with the exact results obtained from the GAMS solver for small scale instances. Also, the computational results of the proposed ACS are compared with a best designed genetic algorithm (GA) for large scale instances to reveal robustness and intelligence of the proposed ACS in comparison with the GA as a competitive algorithm.

The rest of the paper is structured as follows. In Section 2, the resource renting problem with tardiness (RRPT) is described and a mathematical formulation is proposed to it. In Section 3, ant colony system (ACS) based algorithm along with a Genetic Algorithm (GA) with tuned parameters are developed to tackle the RRPT. The computational results and the managerial insights to validate the proposed algorithms are reported in Section 4. Finally, summary of the paper and suggestions for future works are presented in Section 5.

2. Problem definition

The RRPT can be described as follows. Consider a project represented by an activity on node (AON) network $G\left(V, E; \delta\right)$ where V (set of nodes) represents activities, E (set of arcs) represents start to start precedence constraints with a minimal or maximal time-lag and δ (time-lags) denotes the weights of the arcs. The activities are numbered from the dummy start activity 0 to the dummy end activity $n+1$. The set of activities are to be scheduled without preemption on a set of renewable resources, R, where their availabilities and their renting policy are decision variables. For each activity $i \in V$, a fixed duration p_i, a predefined due date h_i, and a known integer resource request r_{ik} of the resource type k during each time unit of its execution are also given. We suppose that $p_0 = p_{n+1} = 0$ and $p_i \geq 0$ and integers, for $i = 1, 2, \ldots, n$. A fixed given deadline $\bar{d}$ is assumed for makespan of the project. Considering an arc $(0, n+1)$ with a weight of $\delta^{max}_{0,n+1} = \bar{d}$, the project's deadline can be preserved. The problem is to find decision vector of the activities' start times, $S = \{s_0, s_1, \ldots, s_{n+1}\}$, and amount of the rented and released resource type k in any time instant t, a_{kt} and w_{kt}, respectively, aimed to minimize availability costs of all the resource types and tardiness penalties of all the activities. Denoting the finish time of activity i as $f_i = s_i + p_i$, tardiness of activity i can be defined as$T_i = \max(0, f_i - h_i)$. Clearly, T_i would be decision variable as a function of s_i through f_i. Let t_i be the unit tardiness penalty of activity i. Each unit of renewable resource type k is rented with a fixed cost of C^p_k and a cost of C^v_k per each time unit of its availability. Also, let to define $h_0 = 0$, $h_{n+1} = \infty$, $t_o = \infty$ and$t_{n+1} = 0$. So, the objective function for minimizing the resources costs and tardiness penalties can be stated as Eq. (1):

$$MinTC = \sum_{k \in R} c^p_k \sum_{t=0}^{\bar{d}} a_{kt} + \sum_{k \in R} c^v_k \sum_{t=0}^{\bar{d}} t\left(w_{kt} - a_{kt}\right) + \sum_{i=0}^{n} t_i T_i \quad (1)$$

For each schedule $S = \{s_0, s_1, \ldots, s_{n+1}\}$ and each renewable resource type $k \in R$, we define $A(S, t) = \left\{i \in V | s_i \leq t \leq s_i + p_i\right\}$ as the set of activities which are in progress in time period t (between time instant $t-1$ and t). So, $r_k(S, t) = \sum_{i \in A(S,t)} r_{ik}$ states the requirement of the resource type k in time period t, which clearly cannot be violated from the available amount of that resource type in time period t. This can be stated in form of constraint set (2):

$$r_k(S, t) \leq \sum_{\tau=0}^{t} \left(a_{k\tau} - w_{k\tau}\right); \forall k \in Randt = 1, \ldots, \bar{d} \quad (2)$$

However, the total amount of the rented and released resource type k must be balanced as stated in Eq. (3):

$$\sum_{t=0}^{\bar{d}} a_{kt} - \sum_{t=0}^{\bar{d}} w_{kt} = 0; \forall k \in R \quad (3)$$

A schedule S will be time feasible if all the minimal and maximal time-lags between start times of the activities be preserved as stated in constraint set (4):

$$s_i + \delta^{min}_{ij} \leq s_j \leq s_i + \delta^{max}_{ij}; \forall (i, j) \in E \quad (4)$$

The expression of $T_i = \max(0, f_i - h_i)$ can be linearly defined in terms of s_i and T_i as constraint set (5):

$$T_i \geq s_i + p_i - h_i and T_i \geq 0; \forall i \in V \quad (5)$$

All the parameters are supposed to be deterministic and except C^p_k, C^v_k and t_i, all of them are integral. Also, all the decision variables, i.e, s_i, T_i, a_{kt} and w_{kt} are integer valued.

A feasible solution satisfying the mentioned constraints in Eqs. (2)–(5) can be described as (S, a, w), where S is the vector of start times, a and w are the matrixes of renting policy. To guarantee the existence of a time feasible schedule, we assume that there is no cycle with a positive length in standard form of the project network [17], where without loss of generality, any maximal time-lag, δ^{max}_{ij}, will be replaced by a backward arc (j, i) with a weight of $\delta_{ji} = -\delta^{max}_{ij}$. The optimal solution for the problem is a feasible solution minimizing total cost of the resources and tardiness costs of the activities expressed in Eq. (1).

Proposition 1. The problem of finding the optimal solution for the RRPT is NP-Hard.

Proof. Consider the special case where $t_i = 0$ for all the activities $i \in V$. Since there is no tardiness penalty, so the RRPT reduces to the classic RRP which is NP-Hard [13]. Thereby, as an extension of the classic RRP, it immediately follows that the RRPT would be NP-hard problem, too □.

Nübel proved that the hardness of the classic RRP is strongly influenced by the ratio of C^v_k / C^p_k. This feature is investigated for the