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Multi-objective metaheuristic algorithms for the resource-constrained project scheduling problem with precedence relations

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ABSTRACT

This study addresses the resource-constrained project scheduling problem with precedence relations, and aims at minimizing two criteria: the makespan and the total weighted start time of the activities. To solve the problem, five multi-objective metaheuristic algorithms are analyzed, based on Multi-objective GRASP (*MOG*), Multi-objective Variable Neighborhood Search (*MOVNS*) and Pareto Iterated Local Search (*PILS*) methods. The proposed algorithms use strategies based on the concept of Pareto Dominance to search for solutions and determine the set of non-dominated solutions. The solutions obtained by the algorithms, from a set of instances adapted from the literature, are compared using four multi-objective performance measures: distance metrics, hypervolume indicator, *epsilon* metric and error ratio. The computational tests have indicated an algorithm based on *MOVNS* as the most efficient one, compared to the distance metrics; also, a combined feature of *MOG* and *MOVNS* appears to be superior compared to the hypervolume and *epsilon* metrics and one based on *PILS* compared to the error ratio. Statistical experiments have shown a significant difference between some proposed algorithms compared to the distance metrics, *epsilon* metric and error ratio. However, significant difference between the proposed algorithms with respect to hypervolume indicator was not observed.

1. Introduction

Scheduling problems have been broadly studied in literature. Among those, the project scheduling (PSP) has been prominent. According to Oguz and Bala [1], the PSP is an important problem and it is challenging for those responsible for project management and for researchers in the related field. As said by the authors, one of the reasons for its importance is that it is a common problem in a great number of real situations of decision making, such as problems that originate in the project management of civil construction. The PSP is challenging, theoretically, for belonging to the class of NP-hard combinatorial optimization problems [2]. Thomas and Salhi [3], for example, state that the optimal solution of the PSP is hard to determine, especially for large-scale problems with resource and precedence constraints.

Despite several authors like Slowinski [4], Martínez-Irano et al. [5] and Ballestín and Blanco [6] consider that the resolution of the PSP involve several and conflicting objectives, few studies have been developed using this approach. According to Ballestín and Blanco [6], the number of possible multi-objective formulations for the PSP is very large, due to the countless objectives found in literature. These can be combined in several forms, thus generating new problems. Among the objectives that project managers are most interested in, according to Ballestín and Blanco [6], we can emphasize the following:

- minimization of the project makespan;
- minimization of the project earliness or lateness;
- minimization of the total project costs;
- minimization of the resources availability costs;
- minimization of the total weighted start time of the activities;
- minimization of the number of tardy activities;
- maximization of the project net present value.

According to Martínez-Irano et al. [5], the multi-objective formulation of a problem is particularly important when the objectives

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are conflicting, i.e., when the objectives may be opposed to one another.

In this work, the PSP with resource and precedence constraints (RCPSPRP) is addressed as a multi-objective optimization problem. Two conflicting objectives are considered in the problem: the makespan minimization and the minimization of the total weighted start time of the activities.

Several multi-objective optimization methods can be found in literature to solve this class of problems. Such methods can be basically divided into two groups: the classic and the metaheuristic methods. The classic methods consist of transforming the objective function vector into a scalar objective function, as it is the case of the Weighted Criteria and the Global Criterion methods. In this case the problem is treated as a mono-objective problem. The metaheuristic methods use metaheuristics to generate and analyze several solutions, as well as to obtain a set of non-dominated solutions. Literature revisions about the multi-objective metaheuristic methods, as published by Jones et al. [7], show the Multi-objective Tabu Search (MOTS) [8], the Pareto Simulated Annealing (PSA) [9], the Non-dominated Sorting Genetic Algorithm II (NSGA-II) [10] and the Strength Pareto Evolutionary Algorithm II (SPEA-II) [11] as the most used. According to Ballestín and Blanco [6], there are still few works that propose efficient methods for solving the multi-objective RCPSPRP. Due to the computational complexity of the RCPSPRP, according to Thomas and Salhi [3], the metaheuristic methods appear as the best form to solve it.

According to Ballestín and Blanco [6], Slowinski [4] was the first author to explicitly represent the RCPSPRP as a multi-objective optimization problem. In the last years, some authors have addressed the RCPSPRP this way, as is the case of Viana and Sousa [12], Kazemi and Tavakkoli-Moghaddan [13], Abbasi et al. [14], Al-Fawzan and Haouari [15], Ballestín and Blanco [6] and Aboutalebi et al. [16].

Recently, new metaheuristic methods have arisen in literature. The main examples are the Multi-objective GRASP (*MOG*) [17], Multi-objective Variable Neighborhood Search (*MOVNS*) [18] and Pareto Iterated Local Search (*PILS*) [19]. Such methods have been applied successfully in several types of problems, as have reported in [20–24]. However, no article was found in literature using these new multi-objective metaheuristic methods to solve the RCPSPRP.

Due to the success of using these new methods, variations of the *MOG*, *MOVNS* and *PILS* are analyzed in this study to solve the RCPSPRP. For this, five algorithms were implemented: a *MOG*, a *MOVNS*, a *MOG* using *VNS* as local search, named *GMOVNS*, a *MOVNS* with an intensification procedure based on [24], named *MOVNS_I*, and a *PILS*. From our knowledge, in terms of algorithms, no work was found using *VNS* as local search for the *MOG*, as was done in the *GMOVNS*.

To assess the efficiency of the implemented algorithms, the results obtained through the use of instances adapted from literature were compared through four multi-objective performance measures: distance metrics, hypervolume indicator, *epsilon* metric, and error ratio. Statistic experiments were also carried out aiming at verifying, if there is a significant difference between the algorithms regarding the used performance measures.

The rest of this paper is organized as following: in Section 2 a literature review is presented. In Section 3 the characteristics of the problem addressed in this study are described and in Section 4 some concepts of the multi-objective optimization are presented. In Section 5 the aforementioned multi-objective metaheuristic algorithms are described, while in Section 6 the characteristics of the instances, as well as the performance measures used to assess and compare the algorithms, are laid out. In Section 6 the results of the conducted tests are presented and analyzed. The last section concludes the work.

2. Literature review

In this section, we briefly describe some important works that have researched the multi-objective RCPSPRP.

Slowinski [4] applied the multi-objective linear programming to solve the multi-mode RCPSPRP, allowing activities preemption. Renewable and non-renewable resources were considered. Makespan and costs minimization were choosing as objectives. In Slowinski's [4] approach, the decision-making is done before the search for solutions. For this, weights were assigned to objectives, which were grouped in a linear objective function. Thus, the decision maker can prioritize one of the objectives. However, this approach present an important disadvantage, the difficulty in defining adequate weights to the objectives. In all the proposed algorithms in our work, the decision-making is done after the search for solutions. That is, a set of candidate solutions (ideally the Pareto-optimal front or an approximation of it) is calculated by the algorithms and then the decision maker selects a solution among them. Also, goal programming and fuzzy logic applications to the multi-objective RCPSPRP were discussed by the author.

The PSA and MOTS algorithms were implemented by Viana and Sousa [12] to solve the multi-objective RCPSPRP. Three minimizing criteria were used: makespan, mean weighted lateness of activities and sum of the violation of resource availability. Due to the lack of multi-objective instances for the problem, adaptations of instances taken from PSPLib were used to test the algorithms. The PSPLib contains numerous mono-objective instances for the RCPSPRP, and adaptations were made to enable the application of multi-objective algorithms. The used instances are composed by 12, 18, 20 and 30 activities and 4 renewable resources. In our work were also made adaptations in instances taken from PSPLib for the application of the proposed algorithms. The average and maximum distance metrics were used to assess and compare the algorithms efficiency. Except for the instances group with 20 activities, the MOTS obtained better results for the used metrics.

Kazemi and Tavakkoli-Moghaddan [13] presented a mathematical model for the multi-objective RCPSPRP considering positive and negative cash flows. The maximization of net present value and makespan minimization were considered as objectives. Weights were assigned to objectives, creating a linear objective function, and one optimization software was used to solve the model. Due to the computational complexity of the RCPSPRP (NP-hard), the use of optimization softwares restricts the tests to instances with small number of activities and resources. The model was tested using four small instances with 12 activities. Kazemi and Tavakkoli-Moghaddan [13] have proposed also the application of NSGA-II to solve the problem. Instances with 10, 12, 14, 16, 18 and 20 activities were used in the computational tests. The instances were taken from PSPLib and adapted to multi-objective optimization.

Abbasi et al. [14] studied the multi-objective RCPSPRP considering two objectives, makespan minimization and robustness maximization. The authors grouped the two objectives in a linear objective function, like in Slowinski [4] and Kazemi and Tavakkoli-Moghaddan [13]. Abbasi et al. [14] described the same difficulty in defining adequate weights to the objectives. However, to generate different solutions for large-scale problems, the Simulated Annealing metaheuristic was used. A numerical example with fifty activities and only one renewable resource was used to illustrate the method.

Al-Fawzan and Haouari [15] have studied the multi-objective RCPSPRP with two objectives, makespan minimization and robustness maximization. A MOTS has been proposed to solve the problem. In the proposed MOTS, the serial schedule generation scheme (S-SGS) was used to generate initial solutions, in the same way as in the algorithms proposed in our work. The difference regarding our work