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Variable neighborhood search with memory for a single-machine scheduling problem with periodic maintenance and sequence-dependent set-up times

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ABSTRACT

In this paper we study the problem of sequencing jobs in a single machine with programmed preventive maintenance and sequence-dependent set-up times. This is an NP-hard problem that has practical relevance because of its industrial applications (textile industry, chemical industry, manufacturing of printed circuit boards, etc.), in which machines need periodic preventive maintenance. An improved formulation of this problem is proposed. Using this new formulation computational experiments show that commercial software can solve exactly not only small-sized instances but also almost all medium-sized instances as well. For solving large-sized instances a heuristic method based on the Variable Neighborhood Search (VNS) is proposed. Specifically, a Skewed VNS with memory, that is, it allows, under certain conditions, the current solution to move to a worse solution and for the incorporation of memory in the search process. Computational experiments show the good performance of our proposed VNS-based method. For small- and medium-sized instances specifically, this method obtains very close-to-optimal solutions, finding the optimal solution in the almost every case. In larger instances our method performs better than previously published algorithms. Several statistical tests support these conclusions. All instances used in computational experiments have been taken from the literature.

1. Introduction

1.1. Motivation

Scheduling optimization methods play a key role in manufacturing performance improvement and cost reduction. Most of the past research in scheduling theory assumes that machines are continuously available. However, in practice unavailability periods often appear due to machine breakdown, preventive maintenance, periodic repairs, or tool changes. Therefore, a more realistic scheduling model should take into account associated machine maintenance activities. Maintenance can reduce the breakdown rate with minor sacrifices in production time. The importance of maintenance has been increasingly recognized by decision makers. In many manufacturing systems maintenance is scheduled regularly or periodically. Therefore, there is a need to develop scheduling methods to deal with periodic maintenance.

Another aspect that should be pointed out consists of the crucial role of setup times/costs in today modern manufacturing. Scheduling activities profoundly depend on the time required to prepare the facility. It has been demonstrated that there are tremendous savings when setup times are explicitly incorporated in scheduling decisions in various real-world industrial/service environments. Furthermore, in some contexts, the setup time for a job may depend on the job that is performed immediately before, for example in industries such as textiles, auto parts, food, chemical, and manufacturing printed circuit boards, among others.

In this paper a single machine scheduling problem is analyzed. This problem includes two simultaneous aspects: preventive maintenance and sequence-dependent setup times. The scheduling problems with preventive maintenance are NP-Hard [31,45]. On the other hand, the scheduling problems with sequence-dependent setup times are strongly related with routing problems and are NP-Hard as well [46]. Additionally, our problem has some features that add more difficulty: the time between two consecutive maintenance activities is previously fixed (and it cannot be modified). Moreover, the jobs cannot be interrupted and resumed. Consequently, there may be idle times. In summary, the problem is an NP-Hard problem with a large degree of computational difficulty.

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This problem, introduced by Angel Bello et al. [3], is very relevant due to its practical applications as well as its computational complexity (as noted above). Specifically, our aim is to improve the previous formulations as well as to propose a new and more efficient heuristic that improves the performance of the methods previously proposed for this problem.

1.2. Related research

Since the mid-1950s, when the first approaches to scheduling problems appeared, many studies have been devoted to analyzing scheduling optimization methods in order to improve manufacturing performance. Some interesting surveys are Yang and Liao [53], Cheng et al. [10], and Potts and Kovalyov [43]. More recent works are Zhang et al. [54,55] and Xu et al. [52].

In the related literature, there are a lot of relevant studies that consider scheduling problems with maintenance activities. Among them, Ji et al. [27], Grigoriev et al. [25], and Liao and Chen [33] considered models with several maintenance activities that are scheduled after a periodic time interval. Other works focused on the problem of scheduling with maintenance activities that should be mentioned are Mosheiov and Sarig [40], Low et al. [35], Chen [8] and Sadfi et al. [49].

All of the previously mentioned works assumed either that there are not setup times or that they are independent of job sequence. The importance of setup times in many applications of scheduling has been investigated in several studies. Allahverdi et al. [2] summarized the works that had appeared in the literature until 2005 about scheduling problems with setup times and real-life applications. More recent works are Lee et al. [30], Wex et al. [51], Kerkhove and Vanhoucke [29], Gawroński [22], and Driessel and Moench [16,17]. However, in some contexts, the setup time for a job may depend of the job that is processed immediately before, for example in the textile industry, manufacturing printed circuit boards, and the chemical industry [7,12,24]. Also in Eren and Güner [20] and Eren [19] flowshop scheduling problems with sequence-dependent setup times were treated. However, none of these works included availability constraints for machines.

The first model that incorporated sequence-dependent setup costs in machine scheduling problems with availability constraints was proposed in Chen [8,9]. These works analyzed a single machine model with sequence-dependent setup times and periodic maintenance. The model has real applications in the textile and manufacturing industries. In this model, a job could be interrupted due to maintenance and the split job will be resumed without any setup time if it is already installed. In addition, there was no setup time for doing a maintenance activity. These two assumptions simplified the problem because the inclusion of maintenance activities did not influence the order in which jobs were processed. On the other hand, in practice, even if the job could be resumed, it would be necessary to carry out certain activities to prepare the machine for maintenance. Then later, after maintenance, the machine would be arranged to continue with the job. In general, these activities depend on the job in process.

In this work, the single- machine scheduling problem with periodic maintenance and sequence-dependent setup times is treated. It aims at scheduling a set of jobs for a single machine, assuming that the machine requires both periodic maintenance and sequence-dependent setup times. The objective is the minimization of the makespan. This NP-hard problem was introduced by Angel Bello et al. [3]. Specifically, this first work showed a mixed integer linear programming (MILP) formulation with a polynomial number of variables and constraints (i.e., a compact formulation), strengthened the formulation with valid inequalities, and initialized the exact algorithm with upper bounds obtained using a heuristic algorithm. The same authors tackled the problem heuristically in Angel Bello et al. [4], using a GRASP. Finally, Pacheco et al. [41] obtained higher quality results for the problem with a multi-start tabu search (TS) metaheuristic and an enhanced version of the compact formulation (CF) presented in Angel Bello et al. [3].

Specifically, the main novelties of this work with respect to the previous ones are the following: 1) a new formulation which can solve to optimality (with commercial software CPLEX) larger instances than the ones solved with previous formulations. 2) Design and implementation of a new heuristic method that significantly improves the results obtained by the previous heuristic methods in larger sized instances. This heuristic method is based on the metaheuristic strategy VNS and its main novelties are the possibility of moving from the current solution to a worse solution (“Skewed” VNS) and the use of memory.

The VNS metaheuristic was proposed initially in Mladenovic [37] and Mladenovic and Hansen [38]. More recent tutorials about this methodology can be found in Mladenović and Melián [39] or Duarte et al. [18]. The VNS approach has already been successfully applied to different job scheduling problems such as in the works of Liao and Cheng [34], Zobolas et al. [56] and Adibi et al. [1]. The variant Skewed VNS was introduced by Hansen et al. [26]. Recent applications can be found in de Souza and Martins [13], Brimberg et al. [6], Dong et al. [15], da Silva Maximiano et al. [11], Macedo et al. [36], and Brimberg et al. [5]. On the other hand, the use of memory in VNS methods can be found in Garcia et al. [21] in the context of linear ordering problems. More recently in Pacheco et al. [42] both tools were combined (Skewed VNS with memory). However, to the best of our knowledge, no methods based on VNS with memory for machine scheduling problems have been proposed so far.

1.3. Contribution

The first contribution is a new MILP formulation of the problem. This formulation is based in the one proposed in Pacheco et al. [41] in which some new valid inequalities are added. These valid inequalities are adaptations of some valid inequalities for routing problems proposed in Desreochers and Laporte [14] and Kara and Bektas [28]. With the previous formulations, the commercial software CPLEX can find optimal solutions only in small-sized instances (up to 15 jobs). With this new formulation, in a moderate amount of time (60 min) CPLEX can obtain optimal solutions in all the instances of the literature of 20 jobs and almost all of the instances of 30 jobs. In the non-solved instances of 30 jobs, it can be concluded that the obtained lower bounds are good, in comparison with the solution obtained by the VNS based method.

On the other hand, we propose a method based on the metaheuristic strategy Variable Neighborhood Search (VNS) for the analyzed problem. Initially, a “Basic” VNS method (BVNS) is designed for this problem. Later, we propose a second method by adding two tools to the BVNS: a) the use of memory in the shaking process, and b) the possibility of moving from the current solution to a worse one. We denote the resultant method as Skewed VNS with Memory (SVNSM). Our proposed VNS methods take some ideas from Pacheco et al. [42]. The computational experiments also show that the SVNSM method is able to reach the optimal solution, or at least very close-to-optimum solutions, in small- and medium-sized instances (up to 30 jobs). It should be highlighted that this comparison with optimal solutions in medium-sized instances is possible due to the use of the new formulation. This formulation allows for solving these instances exactly, or at least for finding good lower bounds. Moreover, SVNSM obtains better results than other heuristic methods previously proposed for this problem in the literature. This improvement is remarkable in large instances. In addition, we have compared both VNS methods. At least in this case, we can conclude that adding memory and using the Skewed

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