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Harmony search algorithm for single-machine scheduling problem with planned maintenance ☆

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ABSTRACT

This paper focuses on the single machine scheduling problem, with sequence dependent setup times. Both processing and setup times are deterministic and the objective is to minimize total earliness and tardiness penalties. The novelty of the model can be traced in the fact that the single machine is subjected to breakdowns and that, in order to increase its availability, planned maintenance tasks are also performed. Hence, jobs and maintenance tasks are jointly considered to find the optimal schedule. These features make the problem NP-hard and so, a quasi-optimal solution is searched using a recent metaheuristic, which integrates *harmony search* and *genetic algorithms*. In order to validate the proposed metaheuristic, a comprehensive set of scheduling problems was fully investigated. Obtained results, compared with those of exhaustive (for small problems) and standard metaheuristics, confirm both the robustness and the speed of the proposed approach.

1. Introduction

In the words by Naderi, Tavakkoli-Moghaddam, and Khalili (2010), production scheduling can be defined as "*the allocation of available production resources to carry out manufacturing tasks in an efficient manner*". In this respect, production scheduling has relevant implications also and especially at the industrial level, but unfortunately, even in its simplest forms, it is an intractable NP-hard optimization problem. Exact methods can be rarely adopted and, for problems of practical interest, the idea of global optimization must be abandoned in favor of the search of good and feasible solutions.

As a matter of fact, as pointed out in the recent literature reviews by Potts and Kovalyov (2000), Ali Allahverdi, Ng, Cheng, and Kovalyov (2008), Lei (2009), Ma, Chu, and Zuo (2010), production scheduling has become a popular playground for the latest heuristic optimization techniques, including all local search paradigms. More specifically, from constructive procedures such as priority-rules (Allahverdi, Gupta, & Aldowaisan, 1999; Lamothe, Marmier, Dupuy, Gaborit, & Dupont, 2012), research interest has shifted to more elaborate techniques like truncated branch and bound, local constraint based analysis, iterative greedy heuristics (Ruiz & Stützle, 2008) and population based meta heuristics (Raza & Al-Turki, 2007; Liu, Wanga, Liud, Qiane, & Jin, 2010; Zhang & Whu, 2010; Jamili, Shafia, & Tavakkoli-Moghaddam, 2011).

What is important to stress is the fact that machines are always considered as fault free, even if, due to breakdowns and to reactive maintenance tasks, this assumption is rather heroic. Also, and perhaps more important, since breakdowns reduce productivity and increase costs, planned maintenance tasks may also be scheduled, as an effective way to improve machines' availability (Nakagawa, 2005). This topic has been recently addressed by an increasing number of papers in the area of the *integrated job maintenance scheduling problem*, in which jobs and maintenance tasks are jointly considered (Safari & Sadjadi, 2011). Research in this field can be traced back to the milestone work by Qi, Chen, and Tu (1999), who was the first one to introduce and solve (by means of branch and bound and heuristics procedures) the single machine integrated job maintenance scheduling problem. Shortly after, Lee and Lin (2001) introduced the idea to link machines' performance to the aging process. This idea has been recently re-proposed by Zhao and Tang (2010) and by Pan, Liao, and Xi (2012), who considered a job-dependent aging ratio and supposed to use sensors and prognostic technologies, so as to constantly monitor machines' conditions.

It is worth noting that, most of the papers in this area focus on the single machine scheduling problem, with sequence dependent setup times. This approach is certainly coherent, because the single

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machine can properly model highly constrained manufacturing environments (such as assembly lines or manufacturing processes), where production must be stopped anytime a failure occur and/or a maintenance task must be performed (Sortrakul & Cassady, 2007).

In this respect, an interesting example can be found in the work by Cassady and Kutanoglu (2003), who developed an analytical approach to optimize the planned maintenance interval, so as to minimize the total weighted tardiness. However, the model was tested using an enumerative approach, but a practical way to use it in real settings was not provided. A more complete framework can be found in the work by Liao and Chen (2003), who considered reduced machine's availability due to deterministic maintenance activities and developed a branch and bound algorithm and a heuristic procedure to minimize maximum tardiness, in case of large size problems, with non-interruptible jobs. Lately, the same problem was also faced by Ji, He, and Cheng (2007) and by Kacem, Chu, and Souissi (2008), who solved it using the Large Processing Time (LPT) algorithm, a mixed integer programming model and a dynamic programming method. One last work that is worth mentioning is the one by Sbihi and Varnier (2008), who focused on the single machine maximum tardiness problem subjected to *periodic* and *flexible periodic* maintenance. Specifically, in case of flexible periodic maintenance, the time interval between consecutive maintenance tasks can change, but the maximum continuous working time allowed to the machine is fixed. Also, in order to solve the problem the authors proposed both a heuristic and a branch-and-bound algorithm.

The need to follow an integrated jobs-maintenance approach is less compelling in more flexible environments, such as job shops, where, in case of failures and of planned maintenance tasks, jobs can be differently routed, without greatly affecting the overall productivity of the system. Anyhow, a limited number of works can also be found in case of parallel machines (Berrichi, Amodeo, Yalaoui, Châtelet, & Mezghiche, 2009) and job-shops (Gao, Gen, & Sun, 2006; Moradi, Fatemi Ghomi, & Zandieh, 2011).

This paper belongs to this stream of research and focuses on the integrated job maintenance single machine scheduling problem, with sequence dependent setup times. The machine is subjected to breakdowns and, in order to increase its availability, planned maintenance tasks are also performed. Processing time, setup times, planned and unplanned maintenance times (i.e., reparations) are deterministic, but the expected number of failures depends both on the aging process of the machine and on the number and on the way in which planned maintenance tasks are scheduled. The objective is to minimize earliness-tardiness penalties or other tardiness related objectives. This is because, as known, tardiness minimization is an objective of great interest both to practitioners and researchers, but it cannot be optimized by any dispatching rule, except in two special cases where setup times are sequence independent, namely: (i) the Shortest Processing Time (SPT) schedule minimizes total tardiness if all jobs are tardy, and (ii) Earliest Due Date (EDD) schedule minimizes total tardiness if at most one job is tardy (Tan, Narasimhan, Rubin, & Ragatz, 2000).

Concerning the solution approach, since the problem is NP-hard, we propose a novel metaheuristic based on the Harmony Search (HS), a recent algorithm in the family of the *population based evolutionary* heuristics (Geem, Kim, & Loganathan, 2001), which has proven its effectiveness in solving NP-hard combinatorial problems (Geem, Lee, & Park, 2005a, 2005b).

The paper is structured as follows. Section 2 introduces the basic notation and gives full details concerning the integrated jobs-maintenances single machine scheduling problem. The metaheuristic used to find a quasi-optimal solution is explained in Sections 3 and it is validated in Sections 4 and 5. To this aim a comprehensive set of scheduling problems is generated and solved, using as benchmark two alternative heuristics (purposely developed to this scope) and a recent simulated annealing developed by Soltani, Jolai, and Zandieh (2010). Lastly, conclusions and directions for future works are given in Section 6.

2. Problem formulation

2.1. Basic single-machine scheduling problem

In production scheduling, the single machine represents the simplest shop configuration. There are N jobs and all of them have a single operation that has to be performed on the single machine of the shop-floor. Also, jobs are assumed to be available at time zero, processing times are deterministic and known in advance and preemption is prohibited. The goal consists in defining the order in which the jobs have to be processed, so as to optimize a user defined objective function.

Specifically, any one of the $N!$ admissible solutions can be denoted as a vector $\pi = (\pi_1, \pi_2, \ldots, \pi_i, \ldots, \pi_N)$ where π_i is a natural number denoting the job that occupies the i-th position of the scheduling sequence.

Now, let:

- $J = \{1, 2, \ldots, N\}$ be the set of the N jobs to be processed,
- $\mathbf{P} = (p_1, p_2, \ldots, p_N)$ be the vector of fixed processing times associated to each job,
- $\mathbf{S} = (s_{ij})$ be the $N \times N$ matrix of the sequence dependent setup times,
- $\mathbf{d} = (d_1, d_2, \ldots, d_N)$ be the vector of the due dates.

Accordingly to this notation the completion time $C_i^{(\pi)}$ of the job scheduled in the i-th position (i.e., π_i) can be obtained as follows:

$$C_i^{(\pi)} = \sum_{k=1}^{i} (s_{\pi_{k-1}\pi_k} + p_{\pi_k}). \tag{1}$$

If $d_{\pi_i} > C_i^{(\pi)}$, then π_i is said to be early, otherwise it is said to be tardy.

Consequently, we can define:

$$T_i^{(\pi)} = \max\left\{0, C_i^{(\pi)} - d_{\pi_i}\right\} \tag{2}$$

and

$$E_i^{(\pi)} = \left|\min\left\{0, C_i^{(\pi)} - d_{\pi_i}\right\}\right| \tag{3}$$

as the Tardiness and the Earliness of job π_i, respectively.

Based on the concepts of Earliness and Tardiness, many objective functions can be defined. Specifically, in the rest of the paper, the following ones will be used to assess the quality of a scheduling sequence:

$$TT = \sum_{i=1}^{N} T_i^{(\pi)}, \tag{4}$$

$$MT = \max_i T_i^{(\pi)}, \tag{5}$$

$$ETP = \sum_{i=1}^{N} \left(a_{\pi_i} \cdot E_i^{(\pi)} + b_{\pi_i} \cdot T_i^{(\pi)}\right) \tag{6}$$

where:

- TT is the Total Tardiness;
- MT is the Maximal Tardiness;
- ETP is the Earliness Tardiness penalties, where a_{π_i} and b_{π_i} are factors used to weight the importance of earliness and tardiness, respectively.