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Parallel machine scheduling to minimize the makespan with sequence dependent deteriorating effects

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ABSTRACT

A new unrelated parallel machine scheduling problem with deteriorating effect and the objective of makespan minimization is presented in this paper. The deterioration of each machine (and therefore of the job processing times) is a function of the sequence of jobs that have been processed by the machine and not (as considered in the literature) by the time at which each job is assigned to the machine or by the number of jobs already processed by the machine. It is showed that for a single machine the problem can be solved in polynomial time, whereas the problem is NP-hard when the number of machines is greater or equal than two. For the last case, a set of list scheduling algorithms and simulated annealing meta-heuristics are designed and the effectiveness of these approaches is evaluated by solving a large number of benchmark instances.

1. Introduction

Research that addresses the scheduling of deteriorating jobs has gained significant popularity in the last two decades. The tenant of problems with deteriorating jobs is that the processing time of the jobs is a function of their start time or the number of jobs since the start of the schedule (or since a maintenance activity), which is again related to the time since the start of the schedule. This paper addresses a variant of the job deterioration problem that considers the case where the deterioration of the processing time for a job depends on the specific jobs that have been previously processed by the machine. This perspective is in line with Yang [1] and Yang et al. [2], where the jobs are not per se deteriorating, but instead the machines are the ones deteriorating, although this differentiation is not made in most models. In our model the deterioration of the machines (and therefore of the job processing time) is a function of the sequence of jobs that have been processed by the same machine and not a function of the two approaches reported in the literature: the time at which the job is assigned to the machine or the number of jobs already processed. Our version of the problem is not yet addressed, and is highly relevant in many practical cases.

Two examples of the proposed relationship between deterioration and job assignment are presented next. The first is the assignment of construction jobs to "work gangs" during a shift. Each job has a baseline processing time, related to the time when all the workers are "fresh". As the workers perform each job they become increasingly tired and therefore their processing speed deteriorates, but this deterioration depends on the particular job sequence. Let us say there are four independent non-sequential jobs, each taking a baseline time of 2 h (each would take 2 h if done first thing in the morning): dig a trench in a hard ground, demolish a shed, clean a storage area, and paint a wall (ordered by effort). While performing the jobs from hardest to easiest may require 9.4 h, performing the jobs from easiest to hardest may require 8.5 h. In the first sequence, the workers may get tired from having performed the first two jobs and therefore take longer time in performing the easy ones. On the other hand, when performing the easy tasks first, they will be "fresh" to complete the exhausting ones.

The second example, similar to that described by Yang et al. [2], considers a shop where machines are used to process a material, for example cutting stock or shredding wood. It can be assumed that depending on the material hardness the tools deteriorate differently. If the jobs with the "softer" material are processed first, the tools will deteriorate less, therefore the tools will maintain a higher level of performance. On the other hand, if the "hard" material jobs are performed first, the tools will deteriorate "faster" and completing the tasks on the softer material jobs take longer, for example if the machine has to be run slower to assure it properly performs the shredding process.

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The remaining of the paper is organized as follows. In the next section, we discuss the recent literature on deteriorating jobs in the parallel machine environment. In Section 3, we formulate the problem for the unrelated machines, show some properties, provide an illustrative example, and finally we present a special case of the problem. In Section 4 we present some heuristics, based on the proprieties showed in Section 3, for the unrelated machines case. An experimental analysis is presented in Section 5. Section 6 concludes the paper and provides suggestions for future research.

2. Literature review

There has been considerable interest in the problem of deteriorating jobs since the seminal work by Gupta and Gupta [3] and Browne and Yechiali [4]. Reviews of the literature for deteriorating job problems have been completed by Alidaee and Womer [5] and by Cheng et. al. [6]. In this section we focus on recent papers in the deteriorating job problem that consider parallel machines environment.

A research stream in the literature characterizes processing time as a function of the job's start time. Let us define p'_j, p_j, t_j, and b_j as the actual processing time, 'baseline processing time', deterioration factor, and start time of job j, respectively. Kang and Ng [7] propose a fully polynomial approximation scheme for the parallel machine problem with makespan objective where the actual processing time is modeled by $p'_j=p_j+b_jt_j$. Kuo and Yang [8] and Toksari and Guner [9] address a variant of the linear version where the increasing (or decreasing) rate is identical for all the jobs (thus $b_j=b$ for all jobs). Kuo and Yang [8] consider the sum of the completion time for all jobs and the sum of the machine completion times as measures of performance, and demonstrate that the problems with processing times represented by two linear functions are polynomially solvable. Toksari and Guner [9] address the objective of minimizing the earliness/tardiness with a common due date. They design a mathematical model for the problem and analyze its performance for solving large problems. Mazdeh et al. [10] consider the parallel machine problem with job deterioration of the form $p'_j=p_j+b_jt_j$ concurrently with the cost of machine deterioration based on the allocation of jobs to the different machines. The authors consider the joint minimization of the total tardiness and the machine deterioration cost. Given the problem is NP-Hard the authors propose a heuristic algorithm and test its effectiveness.

Several researchers address the parallel machine problem when $p'_j=p_jt_j$ with the objective of minimizing the makespan. Ren and Kang [11] present polynomial approximation algorithms for the problem and provide the complexity of the two machine case. Ji and Cheng [12] solve the sum of job completion times problem, while Ji and Cheng [13] address the makespan and sum of machine completion times criteria, proposing approximation algorithms. Cheng et al. [14] address the makespan, but also consider the maximization of the minimum machine completion time. Given both problems are NP-hard, the authors propose heuristic algorithms and evaluate their performance. Huang and Wang [15] address two uncommon objectives: total absolute differences in completion times and the total absolute differences in waiting times. They demonstrate these problems are solvable by polynomial algorithms.

A second research stream in the literature characterizes the processing time as a function of the job's position in the machine sequence. Let us define p'_{jrh} as the processing time of job j if processed in the rth position of machine h. The papers by Yang [1] and Yang et al. [2] consider the parallel machine problem where the actual processing time is defined by one of two models $p'_{jrh}=p_{jh}+r\times b_{jh}$ and $p'_{jrh}=p_{jh}\times r^{b}_{jh}$, where b_{jh} is the deterioration effect of job j on machine h, and the position r depends on the number of jobs after a maintenance event. Both papers address the minimization of the total machine load taking into consideration the joint decisions of maintenance frequency and timing, and the assignment and sequence of the jobs on the machines. The article by Yang [1] deals with the identical parallel machine case, therefore there is no difference in base processing time or deterioration effects between machines, while Yang et al. [2] deal with the unrelated machines (a more general case). In both papers the authors demonstrate that all versions addressed with a given job frequency can be solved in polynomial time.

Mosheiov [16] addresses the general problem where p'_{jrh} is defined as a non-decreasing function in r and the processing time could be unique to each machine, therefore requiring a n^2m input matrix of processing times (where n is the number of jobs and m the number of machines). For this problem the author provides a polynomial time algorithm and describes several extensions. Toksari and Güner [17] combine position based learning with linear and non-linear deterioration with the objective of minimizing the earliness/tardiness with a common due date. They design a mathematical model for the problem and provide a lower bound procedure to address larger problems. On a related problem where the deterioration is neither time dependent nor position dependent, Hsu et al. [18] consider the problem of unrelated parallel machines with rate modifying activities to minimize the total completion time, where at most one rate modifying activity can occur per machine. They propose an algorithm that can solve the problem in $O(n^{m+3})$ if the rate modifying activities are less than 1 (and greater than 0) and in $O(n^{2m+2})$ if the rate modifying activities are larger than 1.

3. The problem

The problem under consideration can be stated as follows. There are n independent jobs, $N=\{1,\ldots j,\ldots n\}$, to be processed on m parallel machines, $M=\{1,\ldots,k,\ldots m\}$. All the jobs are non-preemptive and available for processing at time zero. Each machine can process only one job at a time and cannot stand idle until the last job assigned to it has been finished. There are g possible positions in each machine, $g=n$, and let G be the set of positions. Let p_{jk} be the baseline processing time of job j on machine k. Let d_{jk} be the deteriorating effect of job j on machine k and $0\le d_{jk}<1$ for all $j\in N$ and $k\in M$. Therefore, as in Hsu et al. [18] we include a rate modifying activity, but in our problem each job has a different rate modifying activity.

Let X_k be the ordered set of jobs assigned to machine k, and $x[h,\ k]$ be the job assigned to position h of machine k. Let q_{kh} indicate the performance level of machine k for the job in position h and let q_{kh} be defined by $q_{kh}=(1-d_{x[h-1,k]k})\times q_{k(h-1)}$ for each machine $k\in M$ and each position h greater than 1. It is assumed the machines start with no deterioration, thus $q_{k1}=1$ for all $k\in M$. The actual processing time of the job $x[h,k]$ on machine k is equal to $p'_{x[h,k]k}=p_{x[h,k]k}/q_{kh}$. The problem under consideration is the assignment of jobs to the machines and to sequence the jobs on the machines so that the maximum completion time of all the jobs is minimized.

Let C_k be the completion time of all the jobs assigned to machine k, therefore the sum of the actual processing times for the jobs assigned to the machine. The considered measure of performance is the maximum completion time $C_{max}=max_{\ k\in M}\{C_k\}$. This problem is clearly NP-hard since it reduces to the $P||C_{max}$ problem, which is well known to be NP-Hard, in the class of instances in which the machines are identical and there is no deterioration.