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Decision support for unrelated parallel machine scheduling with discrete controllable processing times

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ABSTRACT

In a manufacturing or service system, the actual processing time of a job can be controlled by the amount of an indivisible resource allocated, such as workers or auxiliary facilities. In this paper, we consider unrelated parallel-machine scheduling problems with discrete controllable processing times. The processing time of a job is discretely controllable by the allocation of indivisible resources. The planner must make decisions on whether or how to allocate resources to jobs during the scheduling horizon to optimize the performance measures. The objective is to minimize the total cost including the cost measured by a standard criterion and the total processing cost. We first consider three scheduling criterions: the total completion time, the total machine load, and the total earliness and tardiness penalties. If the number of machines and the number of possible processing times are fixed, we develop polynomial time algorithms for the considered problems. We then consider the minimization problem of the makespan cost plus the total processing cost and present an integer programming method and a heuristic method to solve the studied problem.

1. Introduction and related works

For the majority of traditional scheduling problems in the literature, the processing times of jobs are assumed to be fixed externally and known in advance over the scheduling horizon. In many realistic systems, however, the job processing times may be variable due to deterioration and/or learning phenomena [27]. Machine scheduling problems with deteriorating jobs and/or learning effects have been paid more attention in recent years; they include [2,12,16,17,19,21,22,29,38,39,42], among others. On the other hand, the job processing times may also be controllable dependent on some additional resources, such as additional energy, fuel, catalysts, budget, or worker, to the job operations. In this situation, both the cost associated with the job schedule and the cost of the resource allocated should be taken into consideration. Therefore, job scheduling and resource allocation should be coordinated carefully and optimized jointly in order to achieve an overall cost-effective schedule [5].

There are two models of scheduling with resource allocations considered in the literature, namely the continuous model and the discrete model [32]. In the continuous resource allocation model, the actual processing time of a job can be controlled by the amount of a divisible resource allocated (e.g., electricity and fuel) and hence can vary continuously in a specific interval. For example, in a manufacturing system the processing time of a job is dependent on the machine running speed which can be controlled to be any number in the interval corresponding to the allocation of the amount of electricity. Van Wassenhove and Baker [33] and Vickson [34,35] were among the pioneers who brought the concept of continuous resource allocation into the field of scheduling. Up to now, a multitude of scheduling problems involving continuous resource allocations has been extensively studied from a variety of perspectives. Nowicki and Zdrzalka [23] studied a two-machine flow shop scheduling problem with controllable job processing times to minimize the total processing cost plus the maximum completion time cost. Panwalkar and Rajagopalan [26] considered the common due-date assignment and single-machine scheduling problem in which the objective function is the sum of penalties based on earliness, tardiness and processing time compressions. Alidaee and Ahmadian [1] extended the problem studied by Panwalkar and Rajagopalan [26] to the parallel-machine scheduling case. Cheng

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et al. [4] investigated unrelated parallel-machine scheduling problems where the job processing times can be compressed by a convex function. Comprehensive surveys on this line of scheduling research with continuous resource allocations can be found in Nowicki and Zdrzalka [24], Chudzik et al. [7], and Shabtay and Steiner [32]. Moreover, some recent papers introduced new models or approaches to scheduling problems with continuous resource allocations. Li et al. [20] investigated a scheduling problem with controllable processing times to minimize the makespan on an identical parallel-machine setting. The critical machine and non-critical machine were considered. They first proposed some theoretical results. And then a simulated annealing algorithm was developed to obtain the near-optimal solutions. Rudek and Rudek [30] considered scheduling problems with the aging effect and additional resource allocation. The following minimization criteria were analyzed: the makespan, the maximum lateness under given resource constraints and the total resource consumption under given constraints on the maximum completion time and the maximum lateness. Rudek and Rudek [31] further studied flowshop scheduling problems with the aging effect and additional resource allocation. The objective was to minimize the makespan. Yin et al. [40] considered single-machine due-window assignment and scheduling with a common flow allowance and controllable processing times. Oron [25] studied single-machine scheduling problems with general linear deterioration and convex resource functions. Yin et al. [41] considered the problem of single-machine batch delivery scheduling with an assignable common due-date and controllable processing times. Yang et al. [36] considered unrelated parallel-machine scheduling with simultaneous considerations of controllable processing times and rate-modifying activities.

In the discrete resource allocation model, the allocated resource is indivisible (e.g., manpower or auxiliary facilities) and hence the actual processing time of a job can only have finitely many possible lengths. For example, in a manufacturing system the processing time of a job is dependent on the allocation of the number of workers, the job processing time can only have finitely many possibilities. Machine scheduling problems with discrete resource allocations have received relatively little attention in the literature. Daniels and Mazzola [10] probably were the first researchers to introduce the discrete resource allocation of processing time in scheduling. They investigated a flowshop scheduling problem where the job processing times are discretely controllable through the allocation of a limited amount of resource. The goal was to minimize the makespan. They gave an optimal algorithm and a heuristic algorithm for solving the problem. Daniels et al. [8,9] studied parallel-machine flexible resource scheduling problems where the processing time of each job is a function of the amount of allocated resource. Both studies were to schedule the jobs on each machine and simultaneously determine the allocation of resource to jobs such that the makespan is minimized. They introduced heuristic algorithms for solving the problems under consideration. Chen et al. [6] considered the discrete resource allocation model in which the job processing times are discretely controllable. They studied a class of single-machine scheduling problems with the objective of minimizing the sum of the total processing cost and the cost measured by a standard criterion. They showed that most scheduling problems with job processing times controlled by resource allocations are NP-hard. Chen [5] explored parallel-machine scheduling problems involving both job processing and resource allocation. The continuous model and the discrete model of resource allocations were examined, respectively. The objective was to minimize the total cost including the cost of a performance measure and the cost of allocated resource. He examined two performance measures of the total weighted completion time and the weighted number of tardy jobs, respectively. He first gave a set partitioning type formulation for the problems and then proposed branch-and-bound algorithms for finding the optimal solutions of the problems. Recently, Grigoriev et al. [15] considered unrelated parallel-machine scheduling problems where the processing time of any job is dependent on the usage of a discrete renewable resource. The objective was to minimize the makespan. They used linear programming techniques to allocate resources to jobs and to assign jobs to machines. Grigoriev and Uetz [14] considered a scheduling problem where n jobs need to be processed on a set of m machines and the processing time of any job is dependent on the usage of a discrete renewable resource. The goal was to find a resource allocation and a corresponding feasible schedule to minimize the makespan. They used a mathematical programming formulation that constitutes a relaxation of the problem. For research results on scheduling with discrete resource allocations, the reader may also refer to the recent survey by Shabtay and Steiner [32].

In this paper, we consider scheduling problems with discrete resource allocations on an unrelated parallel-machine setting where the job processing times are discretely controllable. The planner must make decisions on whether or how to allocate resources to jobs during the scheduling horizon to optimize the performance measures. The objective is to minimize the sum of the total processing cost and the cost measured by a standard criterion. We examine four scheduling criterions: the total completion time, the total machine load, the sum of earliness and tardiness penalties, and the makespan. The motivation for this study stems from an assembly process, a service system, or a project. The production rate (completion time) may improve (reduce) due to the additional of workers, auxiliary facilities, or budgets. As a result, the actual processing time of a job can be controlled by the amount of workers, auxiliary facilities, or budgets.

The remainder of this paper is organized as follows. We formulate the problem under study in Section 2. If the number of machines and the number of possible processing times are fixed, we develop polynomial time algorithms for solving the sum of the total processing cost and the total completion time, the total machine load, and the sum of earliness and tardiness penalties minimization problems in Sections 3–5, respectively. In Section 6, we investigate the minimization problem of the makespan cost plus the total processing cost. We conclude the paper and suggest some topics for future research in the last section.

2. Notations and problem formulation

To facilitate the problem formulation, we introduce the following notations, which are used throughout the paper. Additional notations will be introduced when needed.

m	the number of machines;
M_i	the machine i, $i = 1, 2, \ldots, m$;
n	the number of jobs;
n_i	the number of jobs assigned to machine M_i, $i = 1, 2, \ldots, m$ ($n = \sum_{i=1}^{m} n_i$);
a_{ajh}	the hth possible processing time of job J_j on machine M_i, $i = 1, 2, \ldots, m$, $j = 1, 2, \ldots, n$ and $h = 1, 2, \ldots, k$ ($k \geq 1$ and given);
c_{ijh}	the processing cost associated with each possible processing time a_{ijh};
p_{ij}	the actual processing time of job J_j on machine M_i, $i = 1, 2, \ldots, m$ and $j = 1, 2, \ldots, n$;
$I_{ijh}(p_{ij})$	$I_{ijh}(p_{ij}) = 1$ if $p_{ij} = a_{ijh}$ and $I_{ijh}(p_{ij}) = 0$ otherwise, $i = 1, 2, \ldots, m$, $j = 1, 2, \ldots, n$ and $h = 1, 2, \ldots, k$;
C_{ij}	the completion time of job J_j on machine M_i, $i = 1, 2, \ldots, m$ and $j = 1, 2, ..., n$;
$\sum C_{ij}$	the total completion time;