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Minimizing makespan in a two-machine flowshop with a limited waiting time constraint and sequence-dependent setup times

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ABSTRACT

We consider a two-machine flowshop scheduling problem in which jobs should be processed on the second machine within a certain period of time after those jobs are completed on the first machine, and sequence-dependent setup times are required on the second machine. For the problem with the objective of minimizing makespan, we develop several dominance properties, lower bounds, and heuristic algorithms, and use these to develop a branch and bound algorithm. For evaluation of the performance of the algorithms, computational experiments are performed on randomly generated test instances. Results of the experiments show that the suggested branch and bound algorithm can solve problems with up to 30 jobs in a reasonable amount of CPU time.

1. Introduction

In this study, we consider a two-machine flowshop scheduling problem with limited waiting times and sequence-dependent setup times with objective of minimizing makespan, i.e., the maximum completion time of a given set of jobs. In the problem, the second operation of each job should be started within a certain period of time after the first operation of the job is completed, and the sequence-dependent setup times are incurred between jobs on the second machine. This scheduling problem can be denoted by $F2/s_{ij}$,max-wait/$C_{\max}$ in the three-field notation of Graham et al. [11], where s_{ij} and max-wait mean that sequence-dependent setup times are incurred between jobs and that jobs should be processed on the second machine within a certain period of time after those jobs are completed on the first machine, respectively, and $C_{\max}$ is the makespan. Note that the typical two-machine flowshop is a special case of the problem under consideration.

Scheduling problems with such a limited waiting time constraint can be found in semiconductor wafer fabrication systems, on which our research focus is and where results of this research may be used. Since circuits of semiconductor wafers are very complicated and highly dense, the circuits can be contacted with other circuits by the dust suspended in the air. Moreover, wafers are naturally oxidized if wafers are left in the air for a certain period of time. Also, after a chemical treatment process for a wafer lot is completed on a workstation, the next process for the wafer lot must be started at the next workstation within a pre-determined time period. If the next process for the wafer lots is delayed, it must be abandoned or re-processed because the chemical treatment is no longer effective after the time period [20]. Such a time period between the two processes is called the *limited waiting time* in scheduling research.

Setup times of the jobs are also important in job scheduling research on wafer fabrication systems. A majority of research on flowshop problems is based on the assumption that setup times on each machine are independent of job sequences. However, there are many workstations or processes in which setup times depend on job sequences in wafer fabrication systems. In this study, we develop scheduling algorithms for subsystems of a wafer fabrication system. In the wafer fabrication system, there are many substeps composed of cleaning and diffusion operations. This is because particles and oxide layer on wafers must be removed by the cleaning process before the diffusion process. In the diffusion process, setup times are required to set the temperature of the diffusion machine to the temperature under which wafers should be processed. If a set of wafers has been processed under a low temperature and the next set should be processed under a high temperature, setup times are needed to heat the diffusion machine. In the opposite case, setup times are needed to cool down the machine. Moreover, it is known that setup times depend on how much the temperature should be changed regardless of whether it is heating or cooling. The problem under consideration is modeled from these cleaning and diffusion processes of a wafer fabrication system, and hence we (need to) consider the limited-waiting-time constraint and sequence-dependent setup times.

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Flowshop scheduling problems with sequence-independent setup times have been studied by many researchers [1,12–14,18,21–24,26,27,28,31,32,34,6–8]. However, most of the studies are concerned with scheduling problems with infinite waiting time. Also, if the waiting times of all jobs are zero, the two-machine flowshop problem, which is called the no-wait two-machine flowshop problem, can be solved to optimality with a polynomial time algorithm of Gilmore and Gomory [9]. On the other hand, the problem with arbitrary waiting times is proven to be NP-hard by Yang and Chern [33]. For this problem, several researchers, including Yang and Chern [33] and Bouquard and Lent ´e [5], suggest branch-and-bound (B&B) algorithms with upper bounds and lower bounds. Also, Joo and Kim [20] develop several dominance properties and lower bounds for a B&B algorithm.

Flowshop scheduling problems with sequence-dependent setup times are closely related to the traveling salesman problem (TSP). Therefore, solution properties and solution methods for the TSP can be used for development of solution methods for the scheduling problems with sequence-dependent setup times [10]. Bellman [3] and Held and Karp [17] suggest dynamic programming (DP) formulations for the TSP, or equivalently the single-machine scheduling problem with sequence-dependent setup times. With solution methods for these formulations, one can handle relatively small problems (with 14 or fewer jobs). The two-machine flowshop scheduling problem with no more than 15 jobs can be solved by DP approaches suggested by Bellman et al. [4] and Corwin and Esogbue [10] if setup times depend on the sequence on only one of the two machines. If the setup times are sequence-dependent on both machines, problems with a relatively small number of jobs can be solved by B&B algorithms [15,16]. However, computation times required for the DP algorithms and the B&B algorithms are excessively long even for problems of moderate sizes.

In this paper, we suggest a B&B algorithm for two-machine flowshop scheduling problems with limited waiting time constraints and sequence-dependent setup times for the objective of minimizing makespan. This problem can be easily proven to be NP-hard in the strong sense, since the two-machine flowshop scheduling problem with limited waiting time is NP-hard in the strong sense [33]. For the B&B algorithm, we develop dominance properties, lower bounds, and a heuristic algorithm. Since the problem under consideration is an extended problem of basic two machine flowshop scheduling problem and is closely related to the TSP, we use well-known approaches to those problems and modify and/or combine ideas of those approaches to develop new lower bounds and heuristic algorithms. Therefore, new lower bounds and heuristic algorithm are main contribution of this problem, and dominance properties also help to reduce computation time for solving the problem.

This paper is organized as follows. First, the problem under consideration is more clearly described in the next section. Then, we develop dominance properties, lower bounds, and heuristic algorithms for the problem in Sections 3–5, respectively, and present a B&B algorithm in Section 6. For evaluation of performance of the B&B algorithm, computational experiments are performed on randomly generated instances and results are reported in Section 7. Finally, Section 8 gives a short summary and suggestions for further research.

2. Problem description

In the problem considered here, there are n jobs to be processed on two machines in the order of machine 1 and then machine 2.

The following assumptions are made in this study:

1) At the beginning of the scheduling horizon, there is a given set of jobs to be scheduled during the horizon. (All the jobs are available at time zero.)
2) The processing times of the jobs are known.
3) Each machine can process only one job at a time, and a job can be processed on only one machine at a time.
4) Machines do not fail. (There is no breakdown of machines.)
5) No job can be preempted.
6) After the first operation of a job is completed on the first machine, it must be started on the second machine within a certain period of time, which is called the *waiting time*.
7) Waiting times may be different for different jobs.
8) There are sequence-dependent setup times on the second machine.
9) Sequence-dependent setup times are assumed to be symmetric, that is, setup times between a pair of jobs are the same regardless of the sequence of the two jobs.
10) A setup operation on the second machine can be completed before jobs arrive at the machine.

Effect of the limited waiting time on schedules is shown in Fig. 1, in which there are two different schedules, ones with and without limited waiting time constraints. Because of the limited waiting time constraints, job 2 on machine 1 should be delayed by certain amount of time in case (b) of the figure. Note that job 3 on machine 2 is also delayed for a longer period time in case (b) than in case (a). As a result, makespan of the schedule with limited waiting time constraints is larger than that of the schedule obtained without the constraints.

In this paper, we consider only permutation schedules in which sequences of jobs on the two machines are the same. Although permutation schedules are not dominant in the problem considered in this research, that is, the best permutation schedule may be worse than a non-permutation schedule, permutation schedules are often implemented in practice because of technical restrictions on material handling systems. Note that permutation schedules are dominant in typical two-machine flowshop scheduling problems (without either waiting time constraints or sequence-dependent setup times) with regular measures of performance.

In this paper, we use the following notation:

i, j, m	indices of jobs
k	index of machines $k=1, 2$
$[r]$	index of the job at the rth position in a (partial) schedule
P_{ik}	processing time of job i on machine k,
w_i	waiting time of job i
s_{ij}	sequence-dependent setup time between jobs i and j, $s_{ij}=s_{ji}$
$\boldsymbol{\sigma}$	partial schedule, which is to be placed at the front of a complete schedule

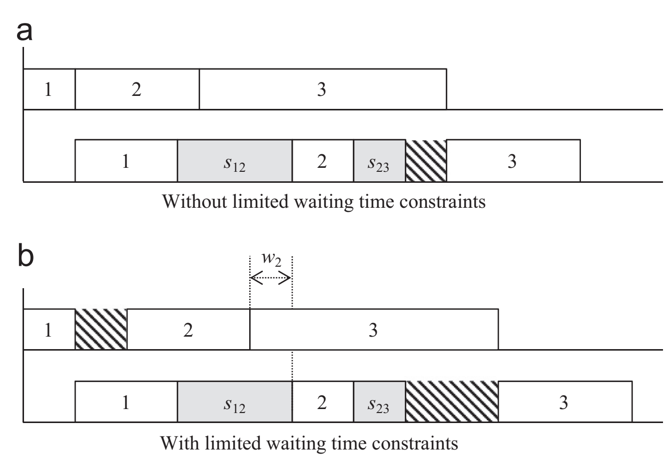

Fig. 1. Schedules with and without limited waiting time constraints: (a) without limited waiting time constraints and (b) with limited waiting time constraints.