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Scheduling jobs with ready times and precedence constraints on parallel batch machines using metaheuristics

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ABSTRACT

In this paper, we discuss a scheduling problem for parallel batch machines where the jobs have ready times. Problems of this type can be found in semiconductor wafer fabrication facilities (wafer fabs). In addition, we consider precedence constraints among the jobs. Such constraints arise, for example, in scheduling subproblems of the shifting bottleneck heuristic when complex job shop scheduling problems are tackled. We use the total weighted tardiness as the performance measure to be optimized. Hence, the problem is NP-hard and we have to rely on heuristic solution approaches. We consider a variable neighborhood search (VNS) scheme and a greedy randomized adaptive search procedure (GRASP) to compute efficient solutions. We assess the performance of the two metaheuristics based on a large set of randomly generated problem instances and based on instances from the literature. The obtained computational results demonstrate that VNS is a very fast heuristic that quickly leads to high-quality solutions, whereas the GRASP is slightly outperformed by the VNS approach. However, the GRASP approach has the advantage that it can be parallelized in a more natural manner compared to VNS.

1. Introduction

Scheduling problems for batch processing machines are important in semiconductor manufacturing because batching operations are much longer compared to non-batching operations (Mathirajan & Sivakumar, 2006). In addition, one third of all operations in wafer fabrication facilities (wafer fabs) are performed on batch processing machines. Hence, the management of batching operations has a large impact on the dynamics of wafer fabs (cf. Mönch, Fowler, Dauzère-Pérès, Mason, & Rose, 2011). In this paper, we consider a batch as a set of jobs that have to be processed at the same time on the same machine.

Diffusion and oxidation machines in wafer fabs are parallel batching machines with incompatible job families. The performance measure to be minimized is the total weighted tardiness (*TWT*). The tardiness of job j is defined as $T_j = \max(0, C_j - d_j)$, where C_j is the completion time and d_j is the due date of job j. The *TWT* measure can be expressed by $TWT = \sum w_j T_j$, where we denote by w_j the weight of job j. We assume that each job has a ready time r_j before which the processing of the job cannot be started. In the context of batching problems, such information is provided by a Manufacturing Execution System (MES). We consider precedence constraints among the jobs. Precedence relations arise when the shifting bottleneck heuristic (SBH) is used to solve the job shop scheduling problem for an entire wafer fab (cf. Mönch, Schabacker, Pabst, & Fowler, 2007). In this situation, we obtain a series of smaller scheduling problems that are parallel batch machine scheduling problems with ready times and precedence constraints where the latter constraints ensure that the disjunctive graph of the SBH does not contain cycles. The researched scheduling problem contains the strongly NP-hard single-machine scheduling problem with TWT measure (cf. Lawler, 1977) as a special case. Therefore, it is also strongly NP-hard.

While several efficient metaheuristics are proposed in the literature for related parallel batch machine scheduling problems with ready times (cf. Chiang, Cheng, & Fu, 2010; Mönch, Balasubramanian, Fowler, & Pfund, 2005 among others) this is not the case when precedence constraints are included. To the best of our knowledge, this type of problem appeared in Mönch et al. (2007), however, the performance of the proposed genetic algorithm was only analyzed implicitly on the entire job shop level.

The contribution of this paper is twofold:

1. We propose a new list scheduling heuristic that clearly outperforms the time window decomposition proposed by Mönch et al. (2005) in the present situation where precedence constraints arise by directly taking into account these constraints.

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2. In addition, we propose and analyze a VNS scheme and a GRASP for the researched batch scheduling problem. The GRASP offers the advantage that it can be parallelized in a rather natural way (cf. Resende & Ribeiro, 2005). Hence, it can serve as a parallelizable subproblem solution procedure (SSP) in the parallel SBH as proposed by Bilyk and Mönch (2012).

The paper is organized as follows. In Section 2, we describe the researched problem and provide a mixed integer programming (MIP) formulation. Related work is discussed in Section 3. Different heuristic approaches including a VNS approach and a GRASP are described in Section 4. The performance of the proposed exact and heuristic approaches is discussed in Section 5.

2. Problem formulation and model

We start by describing the problem. In addition, a MIP formulation for the problem is presented.

2.1. Problem statement

We consider n jobs that have to be scheduled on m identical parallel batch processing machines. The jobs belong to incompatible families that are indexed by $f = 1, \ldots, f_{\max}$. The family of job j is given by $f = f(j)$. All the jobs of the same family f have the identical processing time p_f. We assume that each job j has a ready time $r_j \geqslant 0$. Up to B jobs can be used to form a batch. The quantity B is called the maximum batch size. Only jobs of the same family can be batched together. After a batch is started no preemption of the machine is allowed. We have to take precedence constraints among the jobs into account while minimizing the *TWT* performance measure. It is an important measure for on-time delivery performance.

Using the $\alpha|\beta|\gamma$ notation from scheduling theory (cf. Graham, Lawler, Lenstra, & Rinnooy Kan, 1979), the researched problem can be represented as

$$Pm|r_j, p-batching,\ incompatible,\ prec|TWT, \tag{1}$$

where Pm is used for identical parallel machines, r_j indicates ready times, $p-batching$, $incompatible$ refers to parallel batching with batch availability and incompatible job families, and the term *prec* is used for precedence constraints. Finally, the performance measure used is expressed by the symbol *TWT*.

The following three decisions have to be made to solve an instance of problem (1):

1. Batch formation: Due to the ready times, batches that have less than B jobs might offer some advantage with respect to the *TWT* performance measure.
2. Assigning batches to machines: Each batch has to be assigned to one of the parallel machines.
3. Sequencing batches on individual machines: The sequence of batches has to be determined for each machine.

2.2. MIP formulation

In this subsection, we present a MIP formulation of the scheduling problem (1). The resulting MIP can be used to assess the performance of the proposed heuristics for small-size problem instances. It is similar to the MIP suggested by Klemmt, Weigert, Almeder, and Mönch (2009). Nevertheless, modifications concerning precedence constraints become necessary. The following indices are used in the model:

$i, j = 1, \ldots, n$:	job index
$k = 1, \ldots, m$:	machine index
$b = 1, \ldots, b_{\max}$:	index for batches
$f = 1, \ldots, f_{\max}$:	family index.

The following parameters will be used within the model:

p_j:	processing time of job j
d_j:	due date of job j
r_j:	ready time of job j
w_j:	weight of job j
B:	maximum batch size
$prec_{ij}$:	$\begin{cases} 1, \text{if job } i \text{ has to be a predecessor of job } j \\ 0, \text{otherwise} \end{cases}$
G:	very large positive number.

We use the following decision variables within the model:

s_{bk}:	starting time of the bth batch on machine k
x_{jbk}:	$\begin{cases} 1, \text{ if job } j \text{ is scheduled in the } b\text{th batch} \\ \quad \text{on machine } k \\ 0, \text{ otherwise} \end{cases}$
y_{bkf}:	$\begin{cases} 1, \text{ if all the jobs in the } b\text{th batch on machine} \\ \quad k \text{ belong to family } f \\ 0, \text{ otherwise} \end{cases}$
C_j:	completion time of job j
T_j:	tardiness of job j.

The optimization problem can be formulated as follows where free indices run over their full range if not specified otherwise:

$$\min \sum_{j=1}^{n} w_j T_j \tag{2}$$

subject to

$$\sum_{k=1}^{m} \sum_{b=1}^{b_{\max}} x_{jbk} = 1 \quad \forall j \tag{3}$$

$$\sum_{j=1}^{n} x_{jbk} \leqslant B \quad \forall b, k \tag{4}$$

$$\sum_{l=1}^{f_{\max}} y_{bkl} = 1 \quad \forall b, k \tag{5}$$

$$y_{bkf(j)} - x_{jbk} \geqslant 0 \quad \forall j, b, k \tag{6}$$

$$r_j x_{jbk} \leqslant s_{bk} \quad \forall j, b, k \tag{7}$$

$$s_{bk} + p_j x_{jbk} \leqslant s_{b+1,k} \quad \forall j, b, k \tag{8}$$

$$G(1 - x_{jbk}) + C_j \geqslant s_{bk} + p_j \quad \forall j, b, k \tag{9}$$

$$prec_{ij} C_i \leqslant C_j - p_j \quad \forall i, j \tag{10}$$

$$C_j - T_j \leqslant d_j \quad \forall j \tag{11}$$

$$s_{bk} \geqslant 0,\ x_{jbk} \in \{0, 1\},\ y_{bkf} \in \{0, 1\},\ C_j \geqslant 0,\ T_j \geqslant 0 \quad \forall j, b, k, f. \tag{12}$$