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Heuristic algorithms for scheduling an automated wet-etch station

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Abstract

Wet-etching is a key step in wafer fabrication. A wet-etch station is a chemical batch process involving a complex interplay of mixed intermediate storage (MIS) policies and a shared robot for wafer transfers. Its operation poses a challenging resource-constrained scheduling problem that is crucial for enhancing productivity, improving yield and minimizing contamination. In this paper, we develop three new algorithms for scheduling wafer jobs for a given sequence, which comfortably outperform a literature algorithm in terms of solution quality without requiring excessive effort. Furthermore, we propose a simulated annealing (SA) algorithm for sequencing the wafer jobs. Using this SA algorithm, an existing sequencing algorithm based on tabu search (TS), two job-scheduling algorithms and two algorithms for initial job sequence, we identify eight complete algorithms for scheduling operations in an automated wet-etch station (AWS). After a thorough numerical evaluation, we conclude that the TS sequencing strategy combined with two of our three job-scheduling algorithms is the best option that yields up to 25–30% lower makespans than a literature algorithm, and requires acceptable computing times for industrial-scale problems.

Keywords: Wet-etch station; Multi-product plant; Resource-constrained scheduling; Wafer fabrication; Simulated annealing; Tabu search

1. Introduction

In a previous paper (Bhushan & Karimi, 2003), we developed a novel continuous-time mixed integer linear programming (MILP) formulation for scheduling production in an automated wet-etch station (AWS) and reviewed relevant literature in detail. As discussed there, an AWS performs a key step of wet-etching in wafer fabrication; it removes the exposed or unmasked areas of a wafer. In the AWS, a series of chemical and de-ionizing baths process carriers (jobs) of wafers, while a single robot moves the carriers from bath to bath. These automated movements sharing the single robot and strict requirements on the exposure times of wafers in various baths make the AWS operation complex from a scheduling perspective.

For most scheduling problems, MILP solutions become prohibitive for large problems. Besides, the solution times for MILP algorithms are notoriously sensitive to problem data and unpredictable. Therefore, heuristic methods have been widely reported in the scheduling literature. Although the heuristic methods cannot guarantee optimal solutions, they take much less CPU times and are insensitive to problem data, thus are more reliable and robust for practical application. These factors make them very attractive for solving real-life, large-size, scheduling problems.

For the problem at hand, Geiger, Kempf, and Uzsoy (1997) reported a heuristic algorithm based on tabu search (TS). With the objective of minimizing makespan, they developed an approximate algorithm for scheduling lot transfers by the robot for a given sequence of carriers or jobs on baths. Then, they used this inside a tabu search algorithm to obtain a near-optimal sequence of jobs on the baths. Earlier, Hertz, Mottet, and Rochat (1996) addressed a similar problem occurring in the robotized sample preparation of membrane fatty acid esters for the identification of bacteria. They considered a single product system with 'implicit' and 'explicit' activations of resources. An implicit activation means that a task starts as soon as it enters the resource, while an explicit resource must be turned 'on' to

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Abbreviations: AWS, automated wet-etch station; G, Geiger's robot logic; GA, genetic algorithm; HSP, hoist scheduling problem; II, iterative improvement robot logic; JAT, job-at-a-time; MILP, mixed integer linear programming; MIS, mixed intermediate storage; mNEH, modified Nawaz–Enscore–Ham; NIS, no intermediate storage; SA, simulated annealing; SRPT, shortest remaining processing time; TS, tabu search; ZW, zero-wait

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Nomenclature

$\mathrm{CV_C}$	coefficient of variation of processing times on chemical baths
$\mathrm{CV_W}$	coefficient of variation of processing time on water baths
D_{kj}	minimum delay between jobs q_k and q_{k-1} on bath j to avoid violation of ZW
Dev	percent deviation from the best solution
Imp	improvement upon initial makespan
$\boldsymbol{L}$	robot usage array
$\boldsymbol{L}_\mathrm{T}$	tasks list in $\boldsymbol{L}$
M	number of baths in AWS
MS	makespan
$\mathrm{MS_A}$	final makespan from algorithm A
$\mathrm{MS_{current}}$	current makespan
$\mathrm{MS_I}$	initial makespan
$\mathrm{MS_{new}}$	new makespan
MS^*	minimum makespan
$\Delta\mathrm{MS}$	difference in makespans
N	number of jobs
P	probability of acceptance of a move
$\mathbf{PS}(k)$	plant state prior to the release of q_k to the plant
$\boldsymbol{q}$	job sequence on baths
q_k	job in slot k
q^j	job currently occupying bath j
R_A	iteration number at which the algorithm A hits the minimum solution for the first time
R_min	minimum value of R_A for a test problem
$\boldsymbol{S}$	current plant schedule for $\boldsymbol{q}$
t_{kj}	minimum required processing time of job q_k in bath j
T	temperature
T_{kj}	transfer of q_k to bath j
T_p	temperature at step p
TE_j	earliest time at which q^j can move to $j+1$ without violating the lag required for ZW operation
TE_{j0}	time at which processing of q^j will end on j
TE^*	time at which the SRPT job needs to be moved to the next bath in its recipe
TS_{kj}	time at which job q_k starts processing on bath j
TS^*_{kj}	earliest time at which job q_k can start processing on bath j

Greek letters

π_j	time required to transfer a job from bath j to bath $j+1$
θ_l	element in robot usage array $\boldsymbol{L}$

Subscripts

i	job
j, j'	bath
k, k'	slot in the permutation sequence
l, l'	linked list
p	temperature step

process a job and has to be turned ‘off’ after the job exits. They took into consideration shelf-life constraints and permitted hold-up on the robot. They stressed that defining even a set of feasible schedules and its neighborhood was non-trivial due to the NP-hard nature of the problem. Hence, they used a constraints graph technique to solve this scheduling problem with the objective of minimizing the makespan.

The problem addressed in this paper is more complex than that of Hertz et al. (1996), because it involves a multi-product system in which the robot must ensure zero-wait (ZW) and no intermediate storage (NIS) policies (Ku & Karimi, 1990) at alternate baths. For its solution, we employ a two-level strategy in which the outer or sequencing algorithm examines many job sequences to arrive at the best and the inner or scheduling algorithm computes the makespan for a given sequence by scheduling the movements of jobs among the baths. We present a simulated annealing (SA) (Kalivas, 1995) algorithm for the former and three new algorithms for the latter. Then, we thoroughly evaluate six combinations of algorithms proposed in this paper and those existing in the literature to identify the best two-level algorithm for optimizing operations in the AWS. Finally, we illustrate the application of our algorithms using an example.

2. Problem description

Fig. 1 shows a schematic of the AWS as studied in this paper. It uses a series of M baths ($j = 1-M$) of two alternating types—chemical and water. All odd baths are chemical and each chemical bath precedes a water bath. No inter-bath buffers exist to hold the wafers. Wafers are immersed in each bath for some fixed time. The different reagents in the chemical baths etch away the exposed photo-resist from the wafer layers, and the water in the following de-ionizing or water baths terminates the etching actions by washing the reagents. Overexposure to the reagents can damage a wafer, so the wafer residence times in chemical baths must be controlled strictly. As soon as the required exposure is attained, the wafer must be removed from a chemical bath and “quenched” in the succeeding water bath. On the contrary, overexposure to water does not damage a wafer, so a water bath may hold a wafer beyond its required processing time. These operational constraints are known as the zero-wait policy and the no intermediate storage policy (with local storage on units), respectively, in the batch process