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Sequencing optimisation for makespan improvement at wet-etch tools

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ABSTRACT

The complex nature of wet-etch tools and their peculiar scheduling constraints pose a relevant challenge for the development and implementation of makespan optimisation strategies, especially when rigid scheduling rules have to be considered. In this paper, an optimisation model is developed for sequencing of wafer batches outside a wet-etch tool and scheduling of tool-internal handler moves. The scheduling algorithm is inspired by the control logics governing wet-etch tools operating in a real semiconductor manufacturing plant and proves effective in generating efficient and detailed schedules in short computational times. The mathematical formulation developed for the scheduling problem is based on generic and realistic assumptions for both the job flow and the material handling system. The sequencing module combines an exact optimisation approach, based on an efficient permutation concept, and a heuristics optimisation approach, based on genetic algorithms. The results obtained show that significant makespan reductions can be obtained by means of a mere sequencing optimisation. Using this optimisation strategy, variations to the scheduling logics, that are generally more difficult and expensive to implement, are avoided. A sensitivity analysis on genetic algorithm operators is also conducted and considerations on the best performing selection, cross-over and mutation operators are presented.

1. Introduction

Manufacturing systems characterised by complex interactions between their components are subjected to sensitive dependence on the system status [1,2]; small variations of operating factors, implemented at any production step, may have a significant impact on the overall system performance. As a result, cycle time (CT) reductions obtained at critical production steps could generate considerable productivity improvements and eventually lead to a capacity increase at no investment cost [3,4]. CT improvements also become strategic targets for companies that want to maintain competitive advantages, especially when they operate in highly dynamic industry, such as the semiconductor industry [5].

Wet-etch stations represent critical production steps for the semiconductor wafer manufacturing process [4] as the overall cleaning constitutes almost 10% of the operations in a semiconductor wafer manufacturing plant [6]. A wet-etch station usually consists of several identical wet-etch tools that operate in parallel. Automated wet-etch tools can be classified as batch chamber tools [7]; they include several chambers, or tanks, each of which can accommodate a batch of wafers, usually comprised of one or two lots. Due to the inherent complexities and the peculiar scheduling constraints applied, wet-etch tools are usually modelled using simulation approaches [8]. Simulation models are developed to perform what-if analyses and assess the impact of changes of operational settings on the wet-etch tools performance [9]. Simulation is often integrated with optimisation approaches to identify efficient strategies for operational planning and control of wet-etch tools; simulation-based optimisation has been used to investigate and enhance dispatching and assignment strategies [3,8,9], optimise waiting times for batching operations [8], virtual queue capacity [8,9] and efficient recipe dedication schemes [3,4]. Parallel processing represents one of the most interesting aspects of scheduling related studies at wet etch tools; its effects on CT and throughput have been analysed by Mauer and Schelasin [10] using simulation. They show how the asynchronous batch processing in integrated tools decouples the inversely proportional relationship between CT and throughput so that, due to parallel processing, higher CTs can generate higher throughput and lower overall run time. The model developed in [10] is conceived as a flexible model which can be easily adapted to mimic the behaviour of any type of integrated tools, such as cluster tools. Relevant differences between wet-etch tools and cluster tools exist; however, analogies can be made between the two classes of tools and studies conducted on cluster tools can provide useful insights into the

Abbreviations: CP, constraint programming; CT, cycle time; FIFO, first-in-first-out; GA, genetic algorithm; JAT, job at a time; LS, local storage; MILP, mixed integer linear programming; NIS, no intermediate storage; QT, queuing time; RT, run time; ZW, zero-wait

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Nomenclature

n_i	number of batches requiring operation i
q	batch sequence
q_k	kth batch in the sequence
t_{kc}	processing time of batch k in tank c
$tr_{b\to c}$	transfer time from tank b to tank c
TS_{kc}	time at which batch k enters tank c (i.e., jth tank in its recipe)
TF_{kc}	time at which batch k exits tank c

Greek letters

Φ_d	availability array for tank d
Φ_M	availability data structure for tool M
Φ_R	robot availability array

Subscript

b	tank preceding tank c in batch k recipe (i.e., $(j-1)$th tank in batch k recipe)
c	jth tank in batch k recipe
d	tank following tank c in batch k recipe (i.e., $(j+1)$th tank in batch k recipe)
e	tank following tank c in batch h recipe
i	operation
j	tank sequence order in a recipe
h	batch preceding batch k in a tank
k	batch sequence order and batch

behaviour of wet-etch tools. As an example, a more detailed analysis on the effects of parallel processing on CT can be found in [11] where cluster tools are analysed; a slow-down factor is introduced for approximated predictions on CT delays under different operational settings, such as different start delays, setup times and lot size. More generally, CT analyses at cluster tools with respect to tools configurations [12,13] and sequencing strategies [14] can offer modelling approaches and solutions that could be specifically expanded for wet-etch tools.

Due to the nature of the semiconductor manufacturing process, wet-etch stations are usually followed by furnaces for diffusion processes [15] and, often, the scheduling problem at these two steps is analysed in an integrated fashion. The integrated scheduling problem is characterised by relevant complexities due to the different batch sizes with which the tools operate and the possible presence of wait time constraints between the two processes [16]. Efficient schedules for wet-etch operations prove fundamental to ensure high productivity at the furnaces [17]. Simulation and heuristics are generally used to determine optimal dispatching rules [16–18] and analysing the effects of furnace upgrades on the upstream flow [15,19].

As several operations are performed at a wet-etch tool and parallel processing is allowed, considerable CT savings can be obtained by means of batch sequencing optimisation. Mathematical programming approaches and heuristics have been extensively used for solving sequencing and scheduling optimisation problems at wet-etch stations. For these problems, as a result of management's suggestions, makespan minimisation represents the most common objective function [20]. Indeed, makespan reductions imply increase in throughput and prevent wet-etch tools from becoming a constraint to the factory output [21]. Reducing the makespan also supports an increase in tool capacity and, hence, minimises the number of tools needed, with obvious advantages in terms of occupied clean room floor space [21]. Moreover, decreasing the makespan leads to a lower inventory and contamination and results in greater profits [22]. The observed research trend on wet-etch stations sequencing and scheduling optimisation is towards the development of approaches able to deliver nearly optimal solutions in a reasonable time for increasingly larger sized problems [23]. Less rigid assumptions, especially those regarding the material handling system, are also considered in more recent models [24–27]. Geiger et al. [21] develop a heuristic algorithm based on tabu search for the wet-etch station scheduling problem considering makespan minimisation and blocking constraints at all tanks. Extensive computational experiments are carried out in [21] in order to optimise the tabu search parameters and determine the optimal heuristics to be coupled with the optimisation approach, for generating initial solutions and assessing the solution feasibility. Bhushan and Karimi [22] adopt a mixed integer linear programming (MILP) approach to model a wet-etch station scheduling problem with assumptions similar to those made in [21]. Several formulations of the model, differing between each other for the number of variables and non-essential constraints included, are introduced and their efficiency compared in terms of solution quality and computational time. A re-formulation of the initial MILP model has been proposed by the same authors [28]. In order to generate solutions for larger problem instances, a two-step heuristic approach is also developed; this approach uses the MILP model without the robot-related constraints for generating optimal job sequences and then imposes single-robot restrictions on the sequences in order to make the associated schedules feasible. Further heuristics are proposed by Bhushan and Karimi to address larger instances of the scheduling problem at wet-etch tools with one robot [29]. Two sequencing optimisation approaches, based on tabu search and simulated annealing, are combined with three different scheduling algorithms and the best performing combination exhibited better performance with respect to benchmark problems available in the previous literature. A MILP approach was also recently used in [24] to model the wet-etch tool scheduling problem with several robots; the model proved more efficient than the one developed in [22] for solving medium-sized problems. Analogously to the approach used in [29], a two-step heuristic procedure based on the MILP is developed. As a more efficient alternative to the MILP approach, Zeballos et al. [30] suggest recourse to constraint programming (CP) integrated with a search strategy that speeds up the solution process by guiding the assignment of transport activities to the different robots and reducing the domain of the variables involved in the processing activities. The authors highlight the importance of availing of a search strategy which is tailored to the specific problem in order to make the solution of complex optimisation problems more efficient. Finally, Castro et al. develop an integrated model, based on MILP and discrete event simulation, for solving large-scale wet-etch tool scheduling problems in reasonably short time [23]. Petri nets incorporating conditions for preventing deadlocks and collisions have also been used to model the scheduling problem at wet-etch tools where re-entrant flows are allowed [27,31,32]. MILP is applied to determine robot task sequence and jobs in progress that minimise the cycle time for cyclic schedules [27] whereas various branch and bound algorithms are used to optimise the non-cyclic scheduling problem [31,32].

In the studies reviewed here, the sequencing and scheduling problems are generally analysed as an integrated problem;