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On scheduling a photolithography area containing cluster tools

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ABSTRACT

Photolithography is typically the bottleneck process in semiconductor manufacturing. In this paper, we present a model for optimizing the scheduling of the photolithography process in the presence of both individual and cluster tools. The combination of these individual and cluster tools that process various layers (stages) of the semiconductor manufacturing process flow is a special type of flexible flowshop. We seek separately to minimize total weighted completion time and maximize on-time delivery performance. Experimental results suggest that our solution algorithms show promise for real world implementation as they can help to improve resource utilization, reduce job completion times, and decrease unnecessary delays in a wafer fab.

1. Introduction

Scheduling and sequencing are indispensable processes in industry. A well-designed scheduling system helps the industry focus on increasing throughput by reducing the run time of machines, thereby saving money. Processing jobs on a "first-come, first-serve" basis may not be an optimal policy on the factory floor (Conway, Maxwell, & Miller, 2012). The semiconductor wafer fabrication industry is one of the largest industrial manufacturing segments. Implementing a proper scheduling system in wafer fabrication can help increase profit margins as well as reduce the time required to produce the wafers that contain integrated circuits.

In semiconductor manufacturing, photolithography is normally one of the bottleneck processes that require high capital investments (Sha, Hsu, Che, & Chen, 2006). Hence, optimizing the photolithography process by efficiently scheduling the jobs could be beneficial for the industry. Machines that perform various steps in photolithography can be organized as a flexible flowshop system. A flexible flowshop is defined as a system in which the jobs need to be processed at different sequential stages and at least one of the stages has more than one machine operating in parallel. With the advancement of technology and because of their efficiency and profitability, cluster tools were added to the wafer fabrication processes in recent years. A cluster tool combines various types of machines that perform individual processes and organizes them around a robotic wafer transport device (Yim & Lee, 1999). These tools consist of those machines that are capable of processing two or more stages and combine several processing modules into a single machine (Lee, 2008).

In this research, we develop a scheduling model for the photolithographic process, which is a special type of flexible flowshop (FFS) that has cluster tools along with the traditional individual photolithography tools. According to Chiang (2013), photolithography scheduling is more complex than tradition flexible flowshop scheduling. The author reviews several reasons for this scheduling complexity such as re-entrant job flow, a jobs' readiness, due dates, multiple machine types, multiple orders per job, and lot priorities. Each of the jobs that enter the system typically re-visits equipment visited at earlier manufacturing (*i.e.*, reentrant flow). If the proposed model is tested successfully, it could be implemented in the semiconductor industry that employs photolithography machines with advanced cluster tools. Wafer fabs will be able to schedule their machines to improve utilization of the machines, reduce the processing time for jobs, and efficiently schedule without introducing unnecessary delays in the process.

In short, the key contributions of this paper are:

- To the best of our knowledge, this is the first model that schedule a photolithographic process that consists of both cluster tools and standalone tools with reentrant job flow across multiple product types, job ready times and the continuous flow of jobs inside cluster tools.
- To develop a mixed integer programming model (MIP) to solve this special FFS.
- To implement two heuristic algorithms and compare their performances with respect to the MIP model.

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2. Literature review

Most manufacturing industries face various challenges such as processing high priority jobs, unforeseen breakdowns, scheduled maintenance, delayed processing of jobs, and meeting deadlines set by customers. Proper production planning and process scheduling help to maintain or improve the efficiency of systems and control of operations (Pinedo, 1995). The significance of proper production scheduling comes to light in this scenario when manufacturers need to satisfy customer demands with the help of a minimal number of photolithography tools missing no committed completion time. This committed completion time is the due date (Pinedo, 1995). Montazeri et al. explained and reviewed different scheduling rules, such as static and dynamic rules (Montazeri & Van Wassenhove, 1990). Static and dynamic rules depend on the time when the rule is applied. Static rules, applied at the start of the scheduling period, have a fixed schedule and dynamic rules change as the time progress. The authors also reviews various scheduling rules, compares their performance measures for different environments and conclude that performance evaluation depends on the objective under consideration (Montazeri & Van Wassenhove, 1990).

The four basic processes involved in manufacture of integrated circuits are wafer fabrication, wafer probe, assembly and packaging, and final testing (Uzsoy, Lee, & Martin-Vega, 1992). A wafer fabrication process includes complex procedures and technologies that involve high capital investments. The proper utilization of wafer fabs can lead to increased profit for a semiconductor wafer fabricator. Each time a wafer passes through photolithography, a new layer of required circuitry is formed on the wafer. For most wafers there will be at least 25 such layers. Since the photolithography process is repeated during wafer fabrication, overall performance of the systems is improved by improving the photolithography process (Arisha & Young, 2004). The high capital cost of the photolithography tools forces the wafer manufacturers to streamline the processes to utilize these machines to the fullest possible extent.

There are many literatures and textbooks that explains the machine environments like a single machine, parallel machines, flowshops, job shops, flexible flowshops, and flexible job shops found in industries (Pinedo, 1995). Many mixed-integer programming (MIP) models for scheduling FFS are explained in Sawik (2011). The book considers various scenarios of flowshop modeling with multiple machines in each stage and finite or infinite buffers between each stage. According to Floudas and Lin (2005), many scheduling problems use Mixed Integer Linear Programming (MILP) to find solutions due to their rigorousness, resilience, and flexible design capabilities. Indeed, the use of MIP models is rather popular in this regard.

Ruiz discusses the various solution approaches for the FFS problems, which includes exact methods, heuristics, and meta-heuristics (Ruiz & Vázquez-Rodríguez, 2010). In exact methods approaches such as branch and bound, algorithms solve problems to optimality. The problem with branch-and-bound algorithms is that they utilize a large amount of computer processing resources and are able to solve only problems with a few jobs and stages. Often, they are also deemed to be too complex for real world problems. Lowe and Mason (2016) proposed a deterministic MIP model to schedule weekly production quantities for semiconductor manufacturing in order to meet forecasted demand over a six-month planning horizon. MIP models are proposed in Sawik (2012) for deterministic batch or cyclic scheduling in flow shops with parallel machines and finite in-process buffers. Further, Sawik (2014) presented a new MIP formulation for cyclic scheduling in flow lines with parallel machines and finite in-process buffers, where a Minimal Part Set (MPS) in the same proportion as the overall production target is repetitively scheduled.

A simple, two-stage flexible flowshop is strongly NP-hard (Hoogeveen, Lenstra, & Veltman, 1996). According to Kyparisis and Koulamas (2001), minimizing total weighted completion time for a multiple stage flexible flowshop scheduling problem is NP hard. Hence by extension, the complexity of scheduling a larger flexible flowshop with multiple machines in almost every stage of its processing is also strongly NP hard. When compared to traditional flowshops, a photolithography system involving cluster tools, constraints for multiple wafer routes, reentrant flow, and no buffers inside the cluster tool are therefore also strongly NP hard (Yim & Lee, 1999). Since the practical-sized complex FFS problems NP-hard, we require smart heuristics to arrive at good solutions (Jungwattanakit, Reodecha, Chaovalitwongse, & Werner, 2007).

Solving FFS problems by heuristic methods like dispatching rules and variants of shifting the bottleneck procedure (SBP) (Cheng, Karuno, & Kise, 2001) are explained by Lee (2008). Sarin, Varadarajan, and Wang (2011) provides an overview of advanced dispatching rules and compares the effectiveness of the performance from various simulation studies in a wafer fab. These dispatching rules include scheduling of general wafer fab, specific operations at bay level like photolithography, batch processing, etc. The primary characteristics that make wafer fab scheduling such a different problem includes batching, reentrant flow, sequence dependent setups, and parallel machines (Mönch, Fowler, Dauzère-Pérès, Mason, & Rose, 2011).

Dispatching rules include certain rules of thumb for the priority assignment of jobs onto machines. Some examples of dispatching rules include Shortest Processing Time (SPT), Longest Processing Time (LPT), and Shortest Remaining Processing Time (SRPT). The SBP uses a divide-and-conquer strategy and has been proven very effective when used in combination with exact methods for solving problems. The scheduling of a flexible flowshop with cluster tools is performed via simulated annealing (Yim & Lee, 1999) to obtain a near-optimal solution. However, the study does not consider the re-entry of jobs to previous stages. Pan et al. provide a recent comprehensive literature review of the scheduling of cluster tools in semiconductor manufacturing (Pan, Zhou, Qiao, & Wu, 2018).

Genetic Algorithms (GA) are a popular tool used in a number of papers focused on applications in real-world problems (Oduguwa, Tiwari, & Roy, 2005). GAs have been adapted to solve problems involving sequence-dependent setup times, several production stages with unrelated parallel machines at each stage, and machine eligibility (Ruiz & Maroto, 2006). The choice of how the GA solution is represented is an important facet in the design of a GA, as representation affects other design choices, such as crossover and mutation functions. A commonly employed representation scheme is the topological ordering of the tasks. Ramachandra and Elmaghraby (2006) minimize the weighted sum of completion times in a flexible flowshop by representing the chromosomes as topological orderings of jobs, the schedules of which are obtained using a first-available machine rule for machine assignments.

Table 1 summarizes the relevant literatures. Even though most of the papers reviewed have mentioned either the scheduling of flowshops, the scheduling of flexible flowshops, and/or scheduling of cluster tools separately, there exist no efficient models that analyze a flexible flowshop that contains cluster tools and reentrant job flow across multiple product types. We will also consider job ready times and the continuous flow of jobs inside cluster tools. In this research, we develop a scheduling model for the photolithographic process, that has cluster tools along with traditional photolithography tools, and considers reentrant job flow across multiple product types. Additionally, we use two heuristic algorithms to provide numerical results.

3. Problem description

The photolithography FFS system is arranged in such a way that the individual machines at each stage are organized as a general FFS with a few sets of cluster tools included. As jobs routed through the various stages of the photolithography process could return to one or more of these stages during their processing path, photolithography is a reentrant