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Impact of integrating equipment health in production scheduling for semiconductor fabrication

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ABSTRACT

Monitoring the Equipment Health Indicator (EHI) of critical machines helps effectively to maintain process quality and reduce wafer scrap, rework, and machine breakdowns. To model and illustrate the integration of EHI in scheduling decisions to balance between productivity and quality risk, this paper presents two mixed integer linear programs to schedule jobs on heterogeneous parallel batching machines. The capability of a machine to process a job is categorized as preferred, acceptable, and unfavorable based on the job requirements. The quality risk of processing a job by a machine is a function of its EHI and the capability level of the machine for the job, which is modeled as a penalty in the objective function of trading-off between productivity and quality risk. The first model is static and assumes constant EHI of machines on the scheduling horizon, whereas the second model considers the EHI dynamics, i.e., the machine condition deteriorates over time based on the scheduled jobs. Numerical experiments indicate the potential applications of using EHI-integrated scheduling approaches to analyze and optimize the trade-off between productivity and quality risk.

1. Introduction

Semiconductor wafer fabrication has experienced fast advancement in process technologies and a stringent market environment in the past few decades. Though the worldwide demand is growing, the capital expenditure grows even faster. The cost of a single machine may exceed US$20 million, higher than most other industries (Johnzén, Dauzère-Pérès, & Vialletelle, 2006). Raising manufacturing efficiency via scheduling is therefore a critical and demanding task to maximize the return on investment (Mönch, Fowler, Dauzère-Pérès, Mason, & Rose, 2011).

Scheduling is a function determining when and which wafers are processed by which machine or machine group. Given the delivery requirements from customers, wafers are released in the production line and then processed in a serial flow by different machines. Known as one of the most complex manufacturing processes, each wafer requires hundreds of manufacturing operations in reentrant routes. One wafer visits the same machine groups multiple times in order to form the desired circuitry pattern layer by layer on the wafer surface. This reentrant feature leads to a unique challenge for scheduling because the wafers of either the same or different product types at different layers of fabrication compete for the finite capacity of a machine group.

In the literature, though there are substantial studies on production scheduling (Bitar, Dauzère-Pérès, Yugma, & Roussel, 2016; Bixby, Burda, & Miller, 2006; Chen, 2010; Guo, Jiang, Zhang, & Li, 2012; Kao et al., 2011; Kim & Lee, 2016; Knopp, Dauzère-Pérès, & Yugma, 2017; Koh, Koo, Ha, & Lee, 2004), the status of individual machine is simply set as either up or down, i.e., a binary value, 1 for up and 0 for down, in the Manufacturing Execution System (MES) (Yugma, Blue, Dauzère-Pérès, & Obeid, 2015). State 1 indicates that the machine is available to process the operation and state 0 specifies that the machine is unavailable because of scheduled a Preventive Maintenance (PM) or an unscheduled breakdown. Status of machines is assumed independent of the production schedule. However, advanced process technologies require high conformance to process specifications. Even though the machine is shown as available in the MES, the process quality may not be guaranteed due to the machine deterioration (Chen & Wu, 2007; Sloan & Shanthikumar, 2002).

From a long-term viewpoint, the probability of machine failure naturally increases with the age of the machine (Kamien & Schwartz, 1971). Advanced technologies in semiconductor manufacturing require smaller process tolerances. The dynamic environment, particularly with high product mix and low volumes, increases the difficulty of

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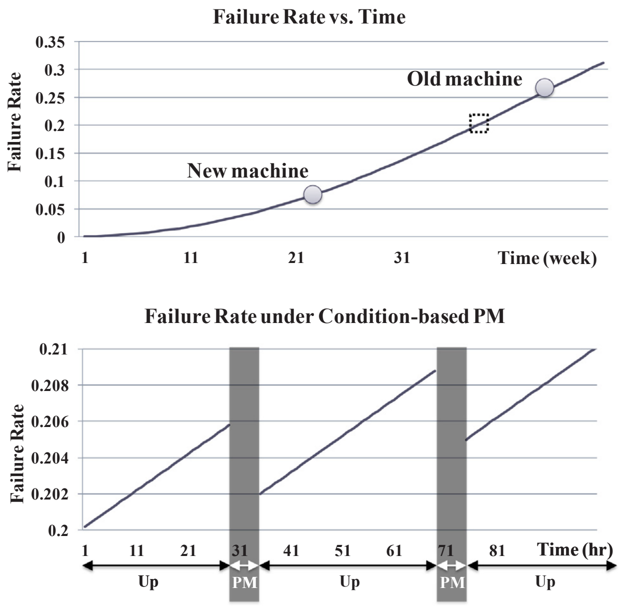

Fig. 1. (a) Long-term machine deterioration increases machine failure probability along time, where a dotted square is magnified in (b) to illustrate the short-term machine deterioration with progressive production.

maintaining the stability of processes. As depicted in Fig. 1(a), older machines have higher failure probabilities than newer ones. In addition, wafer scrap, rework, or unexpected machine breakdown resulting from worn parts will increase production cycle times and decrease productivity. The products which are critical or require a high degree of precision should not be assigned to machines with high failure probabilities, as the product has a high chance to obtain less desired quality after processing. This idea motivates the need to include the level of machine degradation into scheduling decisions.

Apart from long-term degradation, machines also deteriorate on the short term, creating the need for prognosis and health management. For example, particle contamination in a machine may occur after processing some contaminated wafers, which leads to a less-desired machine condition for the following process runs. Monitoring particles in a machine and executing the proper maintenance, i.e., a condition-based (or predictive) maintenance policy, help achieving high system performance with minimum cost instead of a fixed time or count interval to perform Preventive Maintenance, as shown in the enlargement of a dotted square in Fig. 1(a) and 1(b). Many valuable studies have proposed and discussed condition-based maintenance models in the literature (Cheng, Zhou, & Li, 2017; Cui, Lu, Li, & Han, 2018; Grall, Bérenguer, & Dieulle, 2002; Luo, Yan, Hu, Zhou, & Pang, 2015; Yoo & Lee, 2016). A two-level maintenance methodology is proposed in (Xia, Tao, & Xi, 2017) for manufacturing systems, in which machine-level predictive maintenance schedules are first considered and then a variable maintenance time window is used to optimize system-level maintenance. Such condition-based maintenance and health management can further be considered in batching production with variable lot size (Xia, Jin, Xi, & Ni, 2015). Both long and short-term machine deterioration and condition-based maintenance motivate the integration of machine conditions in scheduling decisions.

Considering machine conditions in production has demonstrated significant improvements for a number of operational metrics in semiconductor manufacturing. First, a good maintenance policy helps to reduce the production loss of machines as the unexpected machine failures can be reduced (Jin & Mechehoul, 2010; Luo et al., 2015; Tag & Zhang, 2006; Yu, Lin, & Chien, 2014; Zheng, Zhou, Zheng, & Wu, 2016). For example, machine degradation is modeled as a non-stationary Gaussian process with time-varying mean and variance. The model is then adopted to determine the maintenance schedule for minimizing production cost. Second, the variations between different lots and different chambers can be compensated through proper machine assignment and dispatching (Sloan & Shanthikumar, 2002). A new dispatching criterion is designed to improve the process control of etch depth, which exploits machine variations in the same group obtained from equipment data (Agrawal, Loh, & Shebi, 2015).

Furthermore, machine condition information facilitates improving quality of scheduling decisions. Exploiting degradation modeling and monitoring, Cholette, Celen, Djurdjanovic, and Rasberry (2013) considered preventive maintenance events and production sequencing jointly to design an integrated decision policy, which achieves higher expected profits than a traditional maintenance policy. Kao et al. (2011) adopted a Markov decision process model to include machine deterioration and determine the equipment maintenance and production schedules for maximizing the long-run expected average profit. These works mainly focus on a single tool or a set of homogeneous tools.

Conventionally, machine condition-based job assignment or scheduling mostly relies on the domain experience and knowledge. Some works have recently addressed equipment condition related scheduling problems. For example, machine condition parameters are considered in the optimal schedule to improve yield in Doleschal, Weigert, and Klemmt (2015). But the machine condition is modeled as constant on the whole scheduling horizon, which ignores the fact that the machine condition is changing after processing wafers.

One of the common methods to evaluate the machine condition in the Advanced Process Control (APC) framework is through calculating an Equipment Health Indicator (EHI) (Holfeld, Barlovic, & Good, 2007; Obeid, Dauzère-Pérès, & Yugma, 2012). By monitoring critical machine parameters such as the temperature, voltage, pressure, etc., the overall machine condition can be characterized by some consolidated EHIs. The EHI not only provides an easy reading of the machine performance for engineers but also serves as a basis for improving on production or maintenance policy. To evaluate EHI, several methodologies have been developed in the literature. The multivariate process capability index is commonly used to integrate the multiple parameters into an overall EHI (Chen & Wu, 2007). A recipe-independent EHI and its hierarchical monitoring scheme are further proposed to evaluate the machine health and diagnose the faults systematically (Blue, Gleispach, Roussy, & Scheibelhofer, 2013; Chen & Blue, 2009). Applying EHI in production control helps to identify the machine failures that prolong the production cycle time and to improve the effectiveness of production schedule.

Given the EHI of individual machines and the machine capability requirement of each job based on its criticality, this paper addresses the need of EHI-integrated scheduling over heterogeneous, parallel batching machines. A batching machine is a machine on which a maximum number of jobs (maximum batch size) of the same type can be processed together in a batch with a fixed processing time. When processing times at given stages are much longer than processing times of the upstream stage, the adoption of batching machines is common in practice as it reduces the average job waiting time. For example, most furnaces in wafer manufacturing are batching machines as it takes 4–8 h to heat up, hold the temperature, and then cool down a furnace. But the temperature curve, i.e. capability, may differ between furnaces due to the furnace age, furnace supplier, cumulative processing time after a maintenance, etc. Such long-term degradation and/or short-term deterioration make the furnaces heterogeneous, or unrelated. Heterogeneous parallel batching machines are widely adopted in various industries such as wafer packaging, ceramic sintering or bakeries, making the proposed models extendable to other production systems than wafer manufacturing.

This paper then shows that integrating EHI into production scheduling helps to trade-off decisions between productivity improvement and quality risk reduction. It is obvious that assigning jobs only to a