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Capacitated qualification management in semiconductor manufacturing ☆

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ABSTRACT

In semiconductor manufacturing, machines are usually qualified to process a limited number of recipes related to products. It is possible to qualify recipes on machines to better balance the workload on machines in a given toolset. However, all machines of a toolset do not have equal uptimes and may further suffer from scheduled and unscheduled downtimes. This may heavily impact an efficient recipe-to-machine qualification configuration. In this paper, we propose indicators for recipe-to-machine qualification management based on the overall toolset workload balance under capacity constraints. The models, deployed in industry, demonstrate that the toolset capacity must be considered while managing qualifications. Industrial experiments show how capacity consideration leads to an optimal qualification configuration and therefore capacity utilization.

1. Introduction

The semiconductor industry is one of the most complex and modern industries in the world. Expensive manufacturing equipment and the over-growing competition call for an optimal capacity utilization of the fabrication facilities (called "fabs"). In order to cope with the fast-changing business environment, the production system must be flexible enough to produce a wide range of products, to rapidly manufacture new products or to adapt to product mix changes. This is particularly critical in high mix fabs which have to manage many products with different characteristics and demands.

In semiconductor manufacturing, wafers undergo operations at workstations called "toolset". Each toolset is a collection of unidentical multi-purpose parallel machines that are reconfigurable. For instance, a collection of "furnaces" constitute the "Thermal Treatment Toolset". In order to perform an operation, a *recipe* must be executed on the product. A recipe is the machine instructions to obtain the desired process. For instance, each "implantation recipe" defines the implantation energy, gas (hydrogen, helium, etc.), implantation duration besides other technical specifications. In order to perform an operation on a product, its corresponding recipe must be *qualified* on the machine. However, due to multiple hardware and software restrictions, maintenance or retrofit costs, it is not possible to *qualify* all recipes on every machine. In general, each recipe-to-machine qualification configuration can take one of three cases. When the recipe is not qualifiable on the machine, it is called *unqualifiable*. If the software and hardware specifications of the machine authorize the execution of the recipe on the machine, but the machine is not yet or no longer qualified, the recipe is *qualifiable* on the machine. Without loss of generality, we consider in this paper that all recipe-to-machine couples are either qualifiable or qualified.

The recipe-to-machine qualification configuration has a direct impact on the capacity utilization of the toolset. If the recipe of a product is not qualified on a machine, it is not possible to allocate quantities of the product to that machine. Due to product mix, dynamic fab environment and toolset limited capacity, this may lead to backlog or unsatisfied demand. Therefore, an adequate recipe-to-machine qualification configuration is necessary for the smooth running of the fab [1]. On the other hand, qualifying a qualifiable recipe on a machine can be very time- and energy-consuming. Test products must be used for test runs. Metrology and defect inspection resources must also be extensively used. Hence, it is not economically wise to perform a great number of qualifications. These two contradictory constraints call for an

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efficient *Qualification Management* (QM) policy. Qualifications are also one of the sources of variability.

A machine is not always *productive*. Each machine, depending upon its condition, usage and importance in the production system, has a target productive time. This productive time is referred hereafter to as the *maximum capacity* (or shortly, the *capacity*) of the machine. The capacity of machines in the same toolset may be different, and is dynamic over time due to maintenance plans and many other factors. At each time interval and planning phase, the available capacity of each machine must be considered. Ignoring this important factor while planning may lead to infeasible or inefficient plans. In this study, we take into consideration the capacity of each machine in a toolset for QM. We extend the WIP and time flexibility measures introduced in [2] and, after analyzing these extended measures, we show that additional measures are required.

In Section 2, we cover the literature review on the subject. In Section 3, capacitated indicators used for Qualification Management (QM) are thoroughly discussed. Several solution approaches to the problems are presented in Section 4. Section 5 discusses some industrial experiments and some managerial implications of the study. Finally, we draw conclusions and suggest some perspectives in Section 6.

2. Literature review

For many years, manufacturing flexibility has drawn interest from researchers and practitioners as a key factor of competitiveness in dynamic and uncertain environments. Operation flexibility is defined in [3] as the assignment of production tasks to workcenters, assuming that the number of tasks is larger than the number of workcenters and that the workcenters are able to perform all tasks. Benefits of the defined operations flexibility for a flowshop environment with the objective of minimizing the completion time of all jobs and also maximizing workcenter utilization are studied further.

Early studies consider manufacturing flexibility between plants and products, with various capacity limitations and demands [4]. However, in this paper, we focus on manufacturing flexibility and capacity utilization at the workcenter level, i.e. to which extent the flexibility of recipe-to-machine assignments affects toolset capacity utilization.

Recipe-to-machine QM has come into attention in recent years due to its importance in the semiconductor industry. Here, we discuss the main studies on the subject. Recipe-to-machine qualification configuration is studied as a configuration problem for a parallel multipurpose machines workshop in [5]. The study takes two features into account: demand uncertainty and qualification cost. To hedge against demand uncertainty, the recipe-to-machine qualification configuration must be robust while at the same time, the qualification cost must be minimized. Aubry et al. [6] try to find the qualification configuration at minimum cost in order to balance the workload on the toolset while meeting demand, termed as *load-balanced production plan*. They present a Mixed Integer Linear Program (MILP) for this problem, which is shown to be NP-hard in the strong sense. New indicators, called *Flexibility Measures*, are proposed in [2,7] to estimate the flexibility of the recipe-to-machine qualification configuration of the whole toolset depending upon two different objectives. Two of these measures are recalled in Section 3. An optimization model with binary variables is proposed in [8] with the objective of balancing the workload on all the machines. For each extra qualification, the qualification binary variable is set to 1. Discrete-event simulation has been used in [9] to investigate the impact of the recipe-to-machine qualification configuration and production start volume on the workload of each machine in a toolset. Different simulations are performed with different production start volumes and recipe-to-machine qualification configurations. Using the results of these simulations, the workload of recipes with only one qualification is compared to the workload of recipes qualified on several machines. Generally speaking, capacity planning (or capacity allocation) is seen as critical in semiconductor manufacturing and is still investigated in the literature (see for instance [10–12]).

3. Capacitated flexibility measures

Flexibility measures (FMs) based on two different criteria (*recipe-to-machine configuration robustness* and *toolset workload balance*) are defined in [2] for QM. The*Toolset Flexibility Measure* (Toolset FM) evaluates the *robustness* of a recipe-to-machine qualification configuration. Taking into account capacity in this flexibility measure is not critical and will not be discussed in this paper. The two other FMs are *WIP* (*Work-In-Process*) *Flexibility* and *Time Flexibility*. They aim at *balancing the workload* on the machines in a toolset. The *WIP Flexibility Measure* (WIP FM) evaluates the recipe-to-machine qualification configuration with regard to the workload balance in terms of production volumes (or WIP). The *Time Flexibility Measure* (Time FM) evaluates the qualification configuration with regard to the workload balance in terms of production times. FMs vary between 0 and 1. Higher flexibility values indicate a more effective qualification configuration. In order to evaluate the impact of each extra qualification, the flexibility value of the current qualification configuration is calculated and stored. Then each qualifiable recipe-to-machine couple is virtually qualified, and the resulting qualification configuration flexibility is recalculated and stored. By subtracting the flexibility values for each new configuration from the current configuration flexibility value, the *flexibility gain* of each new qualification is computed.

Note that the *System Flexibility measure* (System FM) introduced in [2] is a combination of *Toolset Flexibility* with either *WIP* or *Time Flexibility* with given weights.

In Section 3.1, we recall the WIP and Time FMs proposed in [2]. These measures assume that all machines have (unlimited) equal capacity. Hereafter, we refer to these FMs as *Uncapacitated Flexibility Measures* (Uncapacitated FMs). By modifying these measures, we define in Section 3.2 new FMs which consider the capacity of each machine. These new FMs are referred to as *Capacitated Flexibility Measures* (Capacited FMs). While taking into account capacity constraints, we show that complementary measures, called *Capacity Deviation Ratio*, are required to appropriately evaluate the qualification configuration of a toolset. These measures are introduced in Section 3.3. In Section 5, we discuss how *Capacitated Flexibility* and *Capacity Deviation Ratio* measures may be used to interpret the workload balancing diagram used for capacity planning.

Below, the *parameters* and *variables* used throughout the paper are defined.

Parameters

- R total number of recipes to be processed,
- M total number of machines in the toolset,
- WIP_r total production volume of recipe r,
- $\text{TP}_{r,m}$ throughput rate of recipe r on machine m (number of wafers per hour),
- Capa_m capacity of each machine m (in hours),
- $Q_{r,m}$ $= \begin{cases} 1 & \text{if recipe } r \text{ is qualified on machine } m, \\ 0 & \text{if recipe } r \text{ is not qualified on machine } m. \end{cases}$
- γ workload balancing exponent ($\gamma \geq 1$).

Variables

- $\text{WIP}_{r,m}$ production volume of recipe r assigned to machine m,
- WIP_m total production volume assigned to machine m ($\text{WIP}_m = \sum_{r=1}^{R} \text{WIP}_{r,m}$).