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MACHINE DEDICATION UNDER PRODUCT AND PROCESS DIVERSITY

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ABSTRACT

Increased product and process diversity in semiconductor manufacturing line has confronted the operations managers with the challenge of managing the setups that usually accompany changes of processes or products at a machine. Recall that under a flexible manufacturing regime, a setup is employed prior to processing in order to prepare the machine with the specific recipe required by the job at hand. Such a setup is performed only if the job last processed by the machine utilized a different recipe.

One way to curtail setups is to divide like machines into groups and dedicate each group of machines to one (or a small number) of recipes. These machine-to-recipe dedications are aimed to eliminate (or reduce) the setups and hence improve productivity. However, these dedications also result in reduced flexibility at operation time and hence serve as a detractor to productivity. To investigate this trade off and evaluate the net effect on productivity, an analytical tool was developed at IBM Microelectronics. In our first set of experiments we confined ourselves to the cases where the number of recipes were equal to the number of machines at the workstation under study. We found that the aforementioned trade off depends largely on two factors: ratio of setup duration to processing duration, and the scheduling policy (Rohan, *Proceedings of the 1999 Western MultiConference*).. This elucidated that the dedication decisions should be independent of the absolute values of setup duration or process duration. Our experiments also indicated that the corresponding break-even points were fairly insensitive to the number of recipes (or machines). In this paper we will relax our assumption regarding recipe to machine equality.

1 DEFINITIONS AND ASSUMPTIONS

1.1 Workstations

In a wafer fabrication plant, lots consisting of several silicon wafers are processed according to a deterministic manufacturing process flow. The process flow for each product may have several hundred steps. Each step is associated with a recipe and a set of similar equipment qualified to perform the designated recipe. This set of equipment is referred to as “workstations” in this paper. A workstation may be associated with a number of different steps in the same process flow or across multiple flows. In our experiments we are concerned only with a single workstation which normally serves several steps.

1.2 Material Movement

Lots, consisting of several wafers, arrive at a workstation as one unit. They enter the workstation’s queue and may have to wait if all machines in that workstation are busy. Once processing commences all wafers are processed by the same machine consecutively (or as a batch). All wafers in the lot must be processed before the lot is allowed to move to the next workstation.

1.3 Conditional Setup

These are setups that must take place only if a lot’s associated recipe is different than the recipe currently set on the machine that is about to process the lot. A recipe usually consists of a) an instruction to the machine (knob setting commonly implemented via a software download to the machine), b) instruction to the operator for hard setups (such as reticle install). A Conditional Setup, apart from the recipe change, may involve follow-up tests and qualification processes (which may or may not require material). Conditional Setups can be as short as a few seconds to equal or longer than the lot’s processing duration. Conditional Setups that are caused by reticle change are said to be the result of “product diversity”. Other Conditional Setups are said to be the result of “process diversity”. Hereinafter we will refer to Conditional Setups simply as “setups”

1.4 $POEE_{CT}$:

Potential Overall Equipment Effectiveness at mean cycle time = CT. As in OEE (Overall Equipment Effectiveness), $POEE_{CT}$ is equal to the fraction of time a machine is processing wafers. That is setup times, equipment down times, and idle periods are deducted from the total time. However, $POOE_{CT}$ differs from OEE in that we assume the machines will never be idle due to demand shortages, hence the term: "Potential" OEE. Since we do not allow market driven demand shortages to impact $POEE_{CT}$, any incurred idle time is strictly due to inherent deficiency of the manufacturing operations, or purposely there to cushion against variability so that our desired cycle time (CT) may be maintained. In a nutshell $POEE_{CT}$ is a measure for intrinsic productivity related to equipment, factory configuration (scale, layout, transport system, etc.), operational methods, and product mix. Furthermore $POEE_{CT}$ is rated for a given service level (mean cycle time is the service level here). Throughout our experiments, we assumed the required cycle time is equal to 3x that of (raw) process duration, so that $POEE_{CT} = POEE_{3xProcess\ Duration}$. Hereinafter whenever the term POEE is mentioned it stands for $POEE_{3xProcess\ Duration}$. The solution that maximizes POEE for a scenario is the optimal solution.

1.5 Other Assumptions

a. Lots' interarrival time variability (Cv_a^2) is equal to 1.
b. Process Durations are the same for all recipes, hence their variability (Cv_s^2) is equal to 0.
c. Conditional Setup Durations are the same for all recipes, hence their variability (Cv_c^2) is equal to 0.
d. There are no machine down times
e. There are no Operators' delays.

These above assumptions are made in order to eliminate the accompanying noise and have clear visibility to the nature of setups / impact of process and product diversity alone.

1.6 Scheduling Rules

Two scheduling rules are examined FCFS (first come first served) and Setup Avoidance. In both cases when there are one or more machines idle (and hence the queue is empty), lot processing takes place when a new lot enters into the workstation. Here, if two or more machines are idle and one of them has the setup for the recipe that the newly arrived lot requires, that machine is selected. When the queue is not empty, the next lot processing occurs when one of the machines completes its previous job. Here, in the case of FCFS rule the lot in front of the queue (longest waited) is selected. If the machine's setup is different than that required by the lot, a Conditional Setup is performed prior to processing the lot. In the case of Setup Avoidance rule if there is no match between the machine setup and the recipe required by the lot in front of the queue, the next oldest lot in the queue is examined for a recipe match, and so until either a) a match is detected, in which case that lot is selected to commence processing - without a conditional setup, or b) the queue is exhausted unsuccessfully, in which case the lot in front of the queue is selected for processing - and processed after the appropriate conditional setup is performed.

2 PRIOR WORK

Previously we showed that when the number of recipes are equal to the number of machines the decision for equipment dedication depends on the scheduling rule and the ratio of setup duration to process duration (Rohan 1999). The setup duration and process duration individually did not play a role. Two rules were examined: FCFS, and Setup Avoidance. Figure 1 shows POEE as a function of Setup Duration to Process Duration for the case with 20 Machines and 20 recipes. The horizontal line (at 80% POEE) corresponds to dedication scenario where each machine is assigned to a single recipe. FCFS and Setup Avoidance would behave in the same manner in this scenario, since no setup will ever occur. The other two curves correspond to the case where all 20 machines are certified to perform any of the 20 recipes (provided the necessary setups are performed whenever a recipe change is required). The FCFS (non dedication) curve intersects the dedication line (horizontal line) at Setup Duration to Process Duration ratio of 24%. Hence, if our workstation has a Setup Duration to Process Duration ratio greater than 24%, we would choose to dedicate each machine to a single recipe. Conversely, if this ratio is smaller than 24% we shall allow all machines to perform all recipes. For the Setup Avoidance case the break-even point is around 77%.

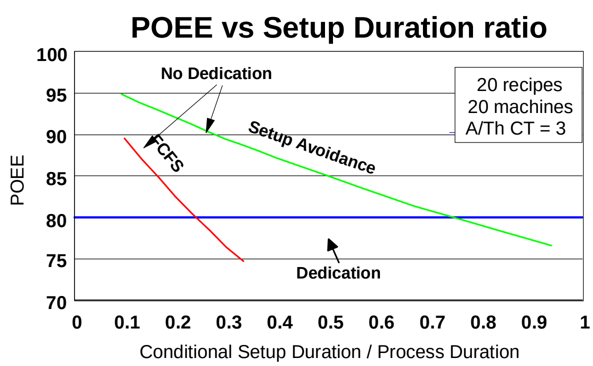


Figure 1: Effectiveness vs. Setup Duration (20 machines and 20 recipes)

When we changed the number of machines and recipes (both) to 3, as shown in Figure 2 we noted that the dedication break-even point for FCFS case stayed remarkably unchanged (at around 21%). The Break-even point for Setup Avoidance rule was slightly altered (down to about 60%). The largely independent nature of these break-even points with respect to the number of machines and recipes pointed to the possibility of developing rule of thumbs for dedication policies that would be both simple and universally applicable.

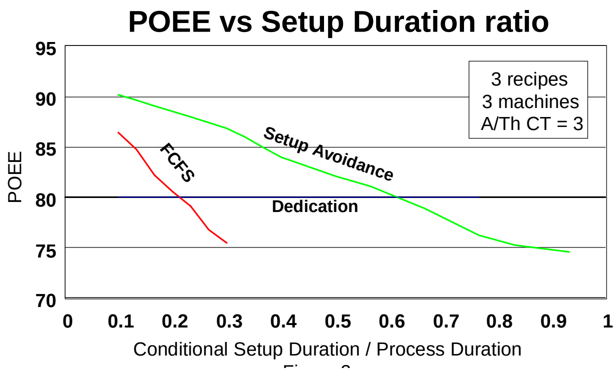


Figure 2: Effectiveness vs. Setup Duration (3 machines and 4 recipes)

3 CURRENT FINDINGS

In the subsequent phase of our research we relaxed the constrain on equality of machines and recipes.

3.1 FCFS Scenario

We first looked at the FCFS case, holding the Setup Duration to Process Duration ratios constant while varying the ratio of number of recipes to the number of. machines. Figure 3 shows two pairs of curves. The top pair corresponds to Setup Duration to Process Duration ratio held at .0667, and the bottom pair correspond to Setup Duration to Process Duration ratio = .1667. We varied the ratio of recipes to machines for each pair from .25 to 1. The curves in each pair correspond to 3 and 20 recipes. For example at Recipes-to-Machines ratio equal to .5 the number of machines are respectively 6 and 40 (so that they yield the same .5 ratio). We noted that the break-even points, that is where

POEE(dedicated) = POEE(non-dedicated),

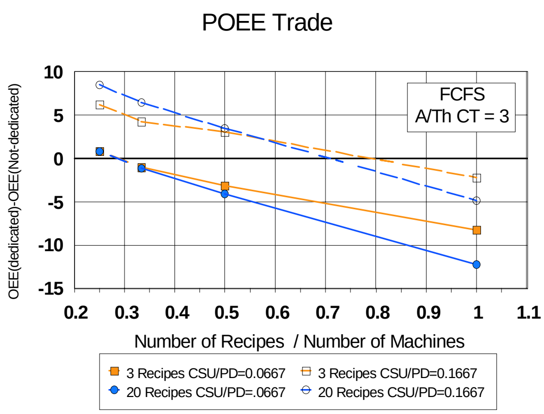


Figure 3: POEE Trade-Off

for the bottom pair (Setup Duration to Process Duration ratio = .0667) occurs at the Recipes-to-Machines ratio of .29, regardless of the number of recipes (or machines). Similarly for the top pair the break-even Recipes-to-Machines ratios were nearly the same (.7 and .77).

This and additional experiments confirmed that (under the FCFS regime) our previous finding about number of machines and recipes not playing a key role individually in determining the break-even point for the case Recipes-to-Machines =1 extends to other cases where Recipes-to-Machines ratios are ≠ 1. In summary the parameters that matter are two:

1. Setup Duration/Process Duration ratio
2. Number of Machines/Number of Recipes ratio

We therefore conjecture that a rule of thumb in the following format may be constructed:

If Setup Duration/Process Duration >
f(Number of Machines/Number of recipes)
dedicate Otherwise do not dedicate

To construct such a function we plotted the break-even Setup Duration to Process Duration ratios against Machines/Recipes ratios for a varity of cases (varying the number of recipes and machines). As expected these variations only altered the curves insignificantly. The cases for 3 and 20 recipes are shown in Figure 4.

We modeled the function ***f*** via a quadratic. Using standard curve fitting techniques we arrived at the following:

$$\boldsymbol{f}(x) = -.098\, x^2 + .344\, x - .021$$

where x is Recipes/Machines ratio. The above equation almost exactly coincides with the tradeoff curves in Figure 4.

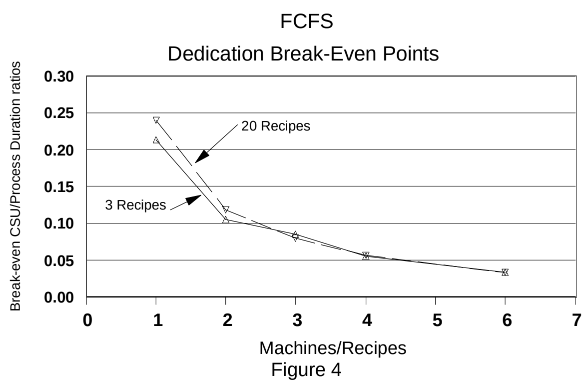


Figure 4: Setup to Process Duration Ratio vs. Machine to Recipes Ratio

The above function can be simplified, without a measurable penalty in accuracy, by dropping the constant term via the following approximation:

$$f(x) = -.005\, x^2 + .23\, x - 0$$

which may be written as:

$$f(x) = x(46-x)/200$$

We observed as the number of machines per recipe increase the break-even Setup to Process Duration ratios decrease, creating a larger incentive to dedicate machines. Conversely as the number of recipes (per machine) increase, the Machine/Recipe ratio decrease, thereby raising the break-even values which translate into less incentive to dedicate.

3.2 Setup Avoidance Scenario

When Setup Avoidance rule is adopted for scheduling, contrary to the FCFS scenario, the break-even curves do not behave uniformly, under different numbers of recipes (and machines). As it can be observed in Figure 5, the case with 3 recipes (the curve in the bottom at left) has a bump at Machines/Recipes ratio = 3. Furthermore this curve is below the curve for the 20 recipes (the solid line at top at the very left) at small Machines/Recipes ratios, but above the 20 recipe curve for larger Machines/Recipes ratios. Additionally, no behavior continuity is observed with respect to the number of recipes (and machines). For example the curve for 7 recipes (dotted line) does not fall between the curves for 3 and 20 recipes - in all regions. The bumps in the curves and the discontinuity in behavior are explainable when the interaction of the contributing components are observed individually. We found them to be due to the juxtaposed nonlinear behavior of setup frequency (see Figure 6) and cycle time as related to congestion. Despite the apparent irregularities, we observed certain commonality in the break-even curves: a) there was a general downward trend as Machines/Recipes ratios increased, b) the bumps appeared once or twice only and, usually deviated from the adjacent break-even points on the same curve by amounts no larger than .2, c) at no time the break-even Setup Duration to Process Duration ratios exceeded .8 .

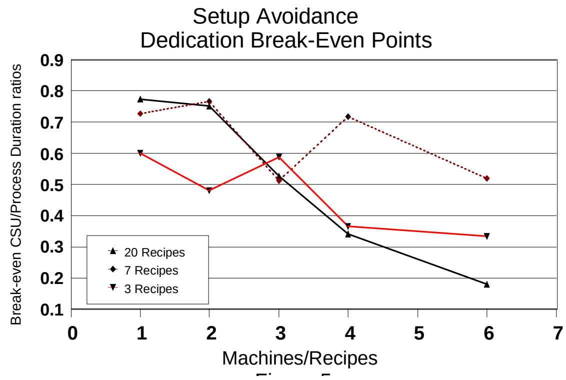


Figure 5

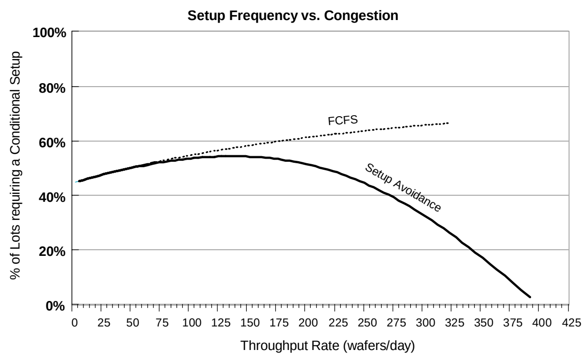


Figure 6: Setup Frequency vs. Throughput Rate

These lead us to hypothesize that .8 may be used as an upper break-even boundary limit for *any* setup duration, process duration, number of recipes, and any number of machines equal to a multiple of the number of recipes, as well as any non-look ahead scheduling rule.

The assertion made above for the scheduling rules stems for two facts:

1. Rules that tend to decrease setups, remove the incentive for dedicating machines to recipes, hence will enjoy larger break-even points.
2. Among the non-look-ahead scheduling rules, Setup Avoidance is capable to minimize setups the most. Recall that a non-look-ahead rule is characterized by a) assignments of lots to machines for processing takes place only for lots that are in the current workstation's queue and only when a machine is ready to process, b) whenever a lot can be processed by a machine an assignment must be made and processing commenced immediately.

When confined to Setup Avoidance, better upper boundaries than .8 (as well as lower boundaries) for dedication decisions may be arrived at. We can do this since the break-even curves are clustered along a narrow downward corridor (as exhibited by the examples in Figure 5). We generated a large number of break-even curves (similar to those in Figure 5) and utilized this data to determine the function:

$$\boldsymbol{g}(x) = -1.2\, x^2 + 1.8\, x + .07$$

for the corridor's centerline (x is Recipes/Machines ratio). The corridor formed by a +.25 and -.2 band around the centerline envelopes the entire region traversed by all the curves.

We also developed the function:

$$\boldsymbol{f}(x) = -1.1271\, x^2 + 1.831\, x - .017$$

to calculate approximate break-even points based on two extreme cases (3 and 20 recipes). This function minimizes the summed absolute errors over the 10 points involved (Machine/Recipes 1, 2,3,4,6 for the two cases: 3 and 20 recipes). The average error was $<\pm.09$, and maximum error $< \pm .14$. This function may be approximated by

$$\boldsymbol{f}(x) \approx -x^2 + 1.72\, x - 0 = x(1.72-x)$$

Figure 7 shows $\boldsymbol{g}(x)$, the surrounding corridor (gray area), $\boldsymbol{f}(x)$ and the corresponding dedication policy.

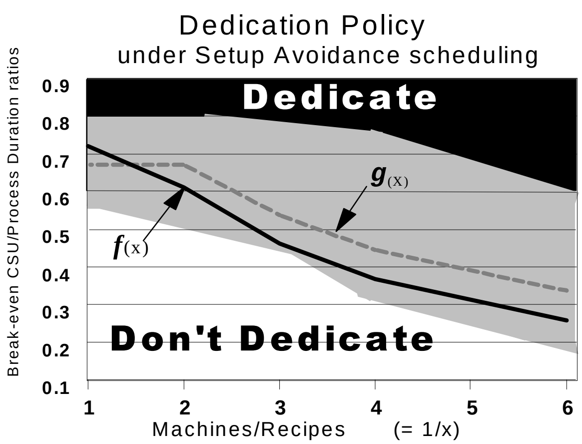


Figure 7: Dedication Policy

4 FUTURE RESEARCH DIRECTION

4.1 Recipes > Machines

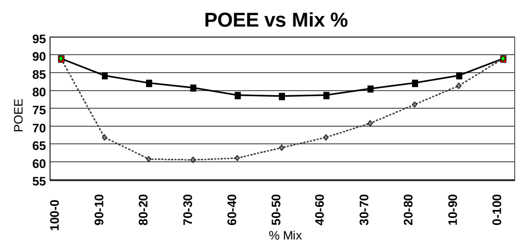
In the work discussed above we examined dedications where number of machines = N x number of recipes (N an integer >1). We plan to extend our research to cases where number of recipes = N x number of machines. In this situation a full dedication (one machine assigned to a single recipe) is never possible, but we could minimize the number of recipes per machine by assigning only N recipes to each machine, and compare this type of dedication to no dedication.

4.2 Unequal Mix

In subsequent phases of our research we shall extend our work to the cases where the mix is not equally divided among the recipes. We know as we move away from an equally divided mix towards a skewed one the negative effect of diversity diminishes. Figure 8 illustrates this via two examples corresponding to the two curves graphed. Both cases involve two recipes. The x-axis shows the mix form 100%-0% (left) to 50%-50% (in the center) to 0-100% (right). The y-axis shows the corresponding POEE. The number of machines is equal to two, and the scheduling rule is an equal mixture of FCFS and Setup Avoidance. The curve at top assumes the two recipes are identical in process duration and setup duration requirements. The curve at the bottom assumes different process duration requirements and longer setups. Clearly the worse POEE is attained at 50-50% mix on the top curve. Where p_j denotes percent mix (in units of lots) for recipes j=1,...J, we have formulated the following index

$$d = \boldsymbol{\Sigma}\, p_j\, (1-p_j)$$

to measure the severity of "diversity". We shall extend the break-even functions $\boldsymbol{f}(x)$ described earlier to $\boldsymbol{f}(x,d)$.



	product 1	product 2
Conditional Setup Duration	1 hr	1 hr
Process Duration	3 hrs	3 hrs

	product 1	product 2
Conditional Setup Duration	2 hrs	2 hrs
Process Duration	1 hr	4 hrs

Figure 8: POEE vs. Mix%

The bottom curve in Figure 8 indicates that severity of mix is highest at the mix that results in equal consumption of machine time by the two recipes. We shall investigate indices that measure severity of mix coherent with this observation, for example:

$$\delta = \boldsymbol{\Sigma}\, \pi_j\, (1-\pi_j)$$

where π_j denote the percent mix in units of processing durations required.

4.3 Recipe to Machine Assignments

Study of unequal mix when number of recipes are greater than the number of machines poses a very real and critical challenge: how should the recipes be assigned to the machines under a maximum dedication policy? We shall propose one such scheme and run experiments comparing it against no dedication.

4.4 The Effect of Cycle Time

In future phases of our research we shall relax the 3x cycle time assumption. Our aim will be to extend the break-even function ***f***(x,d) to account for "required cycle time factor" (CT) by incorporating it as an argument:. ***f***(x,d,CT).

4.5 The Impact of Other Parameters

We will eventually perform sensitivity analysis in the presence of:

1. Variability: process durations, setups, etc...
2. Interruptions: down times and operator delays to examine the suitability of the developed methodologies for practical applications.

4.6 Mixed Strategies

While our research will continue to be focused on the two alternatives corresponding to the two ends of the spectrum in machine to recipe dedication: maximal dedication or no dedication at all, it may well be that a policy of partial dedication is most optimal. In partial dedication certain (or all) recipes will be dedicated to a subset of machines, and the remaining machines will be qualified to process all recipes. We shall briefly study such mixed strategies. In this phase of our research, we shall consider an additional scheduling rule which we call "Least flexible machine preferred". As implied by the name, the machines that have been assigned to specific recipes (and therefore less flexible) will have higher priority. The machines that are not assigned to particular recipes (hence more flexible) shall be more available to serve the recipes that have fewer or no machines assigned to them, under this scheduling regime. We will compare this rule to Setup Avoidance and FCFS.

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DARIUS ROHAN has 20 years of experience in the electronics and semiconductor industry. He has worked in various capacities from manager of Manufacturing Systems department at National Semiconductor to senior member technical staff in the computer science research center and the Operational Methods group at Texas Instruments. He is currently employed at the IBM Technology group, working on microelectronics manufacturing strategy. Mr. Rohan holds a B.S. in Mathematics and an M.S. in Operations Research from Stanford University, and specializes in business modeling, strategy development, and operations optimization.