EVALUATION OF BATCHING STRATEGIES IN A MULTI-PRODUCT WAFERFAB BY DISCRETE-EVENT SIMULATION

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ABSTRACT

In this paper, we present the results of a simulation study for the performance evaluation of certain batching strategies in a multi-product semiconductor wafer fabrication facility (waferfab). Batching in waferfabs means that we can process different lots at the same time on the same machine. As opposite to common scheduling and dispatching decisions in manufacturing beside assignment and sequencing decisions we have to make decisions on the content of a batch. Batching decisions have a large impact on the performance of a waferfab because of very long processing times. In this simulation study, we extend previous work on the evaluation of batching strategies from the two product-case to the case of a larger number of products and different pro duct mix scenarios.

INTRODUCTION

In semiconductor manufacturing, integrated circuits are produced on silicon wafers. This type of manufacturing is very capital intensive. Lots are the moving entities in a waferfab. Each lot contains a fixed number of wafers.
The process conditions are very complex (Uzsoy et al. 1094, Atherton and Atheron 1995, Schönig and Fowler 2000). We have to deal with parallel machines, different types of processes like batch processes and single wafer processes, sequence dependent setup times, prescribed customer due dates for the lots, and reentrant process flows. Very often, we also have to face with an over time changing product mix including a large number of different product.
Batch machines can process several lots at the same time. However lots of different families cannot be processed together due to the chemical nature of the process. Lots that can be processed together form one family. The processing times of batch operations are usually very long compared to other processes. Therefore batching decisions may effect the performance of the entire waferfab. Especially in the case of a multi-product waferfab, the dynamic of the waferfab is influenced by the treatment of batches.
Depending on customer requirements lots of different products have to meet different internal and external due dates. Furthermore, based on customer importance some lots can have a higher weight (priority) than other.
Scheduling and dispatching of batching machines is challenging because beside the common assignment and sequencing decisions batch forming decisions are necessary. Due to unequal ready times of the lots on a certain batch machine (or group of batch machines working in parallel) it is sometimes more favorable to form a non-full batch, in other situation it is better to wait for next lot arrivals in order to increase the fullness of a batch.
Batching issues are intensively discussed in the scheduling and industrial engineering literature. We refer to (Mönch and Habenicht 2003) where some related literature is discussed mainly from a deterministic scheduling point of view. Look-ahead strategies for batching are surveyed by Van der Zee 2003.
The authors study the performance of different dispatching and scheduling heuristics for batching tools with respect to minimize due-date oriented performance measures in (Mönch and Habenicht 2003). This work considers only the rather limited two product-case. However, as pointed out for example by Akçali et al. 2000, the performance of batching strategies can be different in multi-product environments. Therefore, we extend our previous work by performing a simulation study for multi-product waferfabs under different product mix situations.
The paper is organized as follows. In the next section, we summarize two batching heuristics from (Mönch and Habenicht 2003) that are used in this study. Then, we describe the simulation model and our experimental design. We present and discuss the results from simulation experiments in the last section of the paper.

BATCHING ALGORITHMS

In this section, we summarize two batching heuristics from (Mönch and Habenicht 2003) that are relevant for this study. We are interested in two questions. We want to analyze how much we can gain from considering future lot arrivals in a multi-product setting. The second research question is the following one. How does the

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number of lot families influences the performance of our batching strategies?

Notations

We consider one fixed batch tool group. Making a batching decision, we have to decide whether we form a batch only from the set of lots waiting in front of the tool group for processing or to wait for future lot arrivals which means leaving a certain tool idle for a certain period of time. Figure 1 illustrates this issue for a tool group with incompatible families

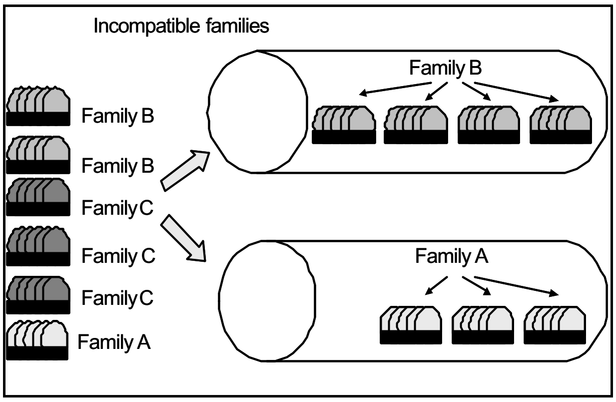

Figure 1: Batching issue with incompatible families

The following notation is used throughout the rest of the paper.

1. Lots belonging to different incompatible families cannot be processed together. The exist F such families.
2. There are n lots that have to be scheduled.
3. The fixed tool group contains m identical machines in parallel. The maximum batch size of the tool group is denoted by B .
4. There are n_j lots of family j to be used for forming and sequencing of batches: $\sum_{j=1}^{F} n_j = n$.
5. Lot i of family j is represented as ij .
6. The priority weight for lot i belonging to family j is represented as w_{ij} .
7. The ready time of lot i in family j is denoted by r_{ij} .
8. The due date (with respect to the batching tool group) of lot i of family j is represented as d_{ij} .
9. The completion time of lot i of family j on the batching tool group is represented as c_{ij} .
10. The processing time of lots in family j is denoted by p_j .

We use the notation $x^+ = \max(0, x)$ for abbreviation. We frequently refer to the total weighted tardiness as performance measure (with respect to a fixed tool group) for a given schedule. This measure is defined as follows:

$$TWT := \sum w_{ij} \left(c_{ij} - d_{ij}\right)^+ . \qquad (1)$$

Static Batch Dispatching Heuristic (SBDH)

The first heuristic is a modification of the well-known Apparent Tardiness Cost Dispatching Rule (Vepsalainen and Morton 1987). In the work of Mason et al. 2002 this rule was adapted to the scheduling of batch machines. We calculate the static batch ATC index $I_{ij,stat}(t)$ for job i belonging to family j at time t

$$I_{ij,stat} = \frac{w_{ij}}{p_j} \exp\left(- \frac{\left(d_{ij} - p_j - t\right)^+}{k\overline{p}} \right). \qquad (2)$$

The parameter k is a scaling parameter and $\overline{p}$ represents the average processing time of the remaining jobs. We sequence the lots of one family waiting in front of the batch tool group in descending order with respect to their $I_{ij,stat}(t)$ index. We take the first B lots of this sequence in order to form the batch that has to be processed next for this family. We choose the batch with highest sum of the $I_{ij,stat}(t)$ indices of the lots of the batch among the families. This batch will be processed next.

For the purpose of finding an optimal k parameter with respect to the total weighted tardiness of the lot waiting for processing, we repeat the calculation for different values of k and choose for implementation the schedule that leads to the smallest TWT value.

This heuristic is a full-size batch strategy and does not take any future lot arrivals into account.

Dynamic Batch Dispatching Heuristic (DBDH)

The second heuristic takes future lot arrivals into account. Therefore, we define a time window $(t, t + \Delta t)$. Usually, we chose a fixed portion of the average processing time of the waiting lot as Δt . The set of lots from family j that are ready for processing at time t or will arrive inside the given window is denoted by

$$M(j, t, \Delta t) := \{ij / r_{ij} \le t + \Delta t\}. \qquad (3)$$

The elements of $M(i, t, \Delta t)$ are sorted in descending order with respect to the index

$$I_{ij,dyn}(t) = \frac{w_{ij}}{p_j} \exp\left(- \frac{\left(d_{ij} - p_j - t + \left(r_{ij} - t\right)^+\right)^+}{k\overline{p}} \right). \qquad (4)$$

In the next steps, we only consider the first $\#lots$ lots of the sorted set $M(i,t,\Delta t)$. Here, $\#lots$ is a fixed number that is a parameter of the heuristic. We build all batch combination using these lots. We calculate the batch index

$$I_{bj}(t)=\frac{w_{bj}}{p_j}\exp\left(-\frac{(sl+rt)^+}{k\bar{p}}\right)\min\left(\frac{n_{bj}}{B},1\right) \quad (5)$$

for each formed batch. Therefore we denote by
$d_{bj} := \min_{i\in B_{bj}} (d_{ij})$: minimum due date among all jobs belonging to the batch,
$r_{bj} := \max_{i\in B_j} (r_{ij})$: maximum ready time of the jobs assigned to the batch,
w_{bj}: average weight of the lots contained in the batch,
n_{bj}: number of lots in the batch.
For abbreviation, we use $sl := d_{bj} - p_j - t$ and $rt := (r_{bj} - t)^+$.
This strategy does not necessarily form full batches. Sometimes, it is more profitable to wait for an important lot instead of processing a batch with unimportant lots. From the previous study (Mönch and Habenicht 2003), it is known that DBDH is sensitive to the size of the time window and to the parameter #lots.

EXPERIMENTAL DESIGN

Framework for Experimentation

We use a discrete-event simulation tool and a simulation model of a waferfab to evaluate SBDH and DBDH. Our basic architecture is described by (Mönch et al. 2002). The center point is a data storage (called data model) which contains all information required to run the dispatching and scheduling algorithms. We extend the data model by additional classes and attributes to adapt it to the two algorithms. The data model connects the manufacturing process emulated by the simulation tool and the proposed production control schemes.
We use the MIMAC test data set 1 (Fowler and Robinson 1995) in a modified version. The original model consists of two different product flows (A, B) with about 200 process steps and more than 80 tool groups. We create new product flows based on product flow A and B to build a multi-product environment.
The simulation model contains 16 batching tool groups. Tool group OXIDE_1 is bottleneck of the waferfab. In Table 1, information of this batching tool group are provided.

Table 1: Bottleneck Batching Tool Group Information

Tool Group	# tools	B_{min}	B_{max}	p_{min}	p_{max}	Utilization [%]
OXIDE_1	3	2	6	135	1410	84.19

In Table 1, we denote by B_{min} the minimum batch size and by B_{max} the maximum batch size given in lots. The minimum processing time (measured in minutes) is represented by p_{min} and the corresponding maximum processing time by p_{max}. The given utilization of the tool group was determined by simulation experiments with the First In First Out (FIFO) dispatching rule. We decided to apply the SBDH and DBDH rule to this tool group.
For the remaining tool groups, we used a slack-based dispatching rule (SLACK). For the calculation of the slack of the lots waiting in front of a certain tool group we calculate a schedule by simply multiplying the processing time of the steps with a dynamic flow factor. For that purpose, we calculate the remaining time of the lot with respect to the due date. Based on this information, we assign a flow factor to each lot (cf. Habenicht and Mönch 2002 for more details). This scheduling method allows us to determine the end dates of the single process steps, in particular future lot arrival information. The end dates serves as internal due dates. We repeat the calculation of the flow factors every 24 hours.
In our experiments we use a moderate workload of the system. Machine failures are exponentially distributed. The model is initialized by using a work in process distribution of the waferfab. The length of a simulation run was 100 days. We take five independent replications of each simulation run in order to obtain statistically significant results.

Performance Measures

The following performance measures are used:

- Total weighted tardiness (with respect to the entire waferfab) of the lots that are released and finished within the planning horizon under consideration. We define the weighted tardiness of a lot i as follows:

$$T_i := w_i\left(C_i^r - d_i\right)^+, \quad (6)$$

  where C_i^r represents the realized completion time, d_i the due date and w_i the weight of the lot i. In order to calculate the performance measure we sum the T_i for all lots. We denote this quantity by TWT_{total}.
- Average cycle time: CT.
- Throughput of the waferfab (number of completed wafers): TP.

Design of Experiments

In (Mönch and Habenicht 2003) we studied the behavior of the batching heuristics under different system condition. We identified different parameters which influence the performance of the batching heuristics. We distinguish two groups of parameters. The first group of parameter characterizes the manufacturing systems:

- number of incompatible families,
- due date settings,

- weight settings.

Parameters that are used for settings in the heuristic, especially the DBDH rule, belong to the second group:

- length of the time window,
- maximum number of lots used for considering all batch combinations,
- setting of the parameter k .

In (Habenicht and Mönch 2003), we limited the number of families by considering only two products. In this paper, we extend these investigations by considering more products. In our experiments, we vary the time window settings as exclusive parameter of the second group. We fix the other parameters of the heuristics by investigating only the case of optimal k value setting as described before. The maximum number of lots *#lots* used for considering all batch combinations is ten. The due date is chosen by using a fixed flow factor of two. We consider the case of two, eight, and sixteen different products. An incompatible family is formed by all lots of the a product.

The used factorial design is summarized in Table 2.

Table 2: Factorial Design for this Study

<table>
<tr><td rowspan="2">Factor</td><td colspan="3">Level</td></tr>
<tr><td>I</td><td>II</td><td>III</td></tr>
<tr><td>Number of Products</td><td>2</td><td>8</td><td>16</td></tr>
<tr><td rowspan="2">Factor</td><td colspan="3">Level</td></tr>
<tr><td>I</td><td colspan="2">II</td></tr>
<tr><td>Relation of Product Appearance</td><td>1:1</td><td colspan="2">2:1</td></tr>
<tr><td>Weight</td><td>With probability:
$p_1 = 0.7$
$w_j = 1$
with probability:
$p_1 = 0.25$
$w_j = 3$
with probability:
$p_1 = 0.05$
$w_j = 10$</td><td colspan="2">With probability:
$p_1 = 0.5$
$w_j = 1$
with probability:
$p_1 = 0.3$
$w_j = 3$
with probability:
$p_1 = 0.2$
$w_j = 10$</td></tr>
<tr><td>Time Window Size</td><td>25% of the average processing time of the lots queuing in front of the batching tools</td><td colspan="2">50% of the average processing time of the lots queuing in front of the batching tools</td></tr>
</table>

For the case of eight products, we copy product flow A and B four times and for sixteen products eight times respectively. Each product flow, created in this way, represents a certain product.

Using DHBH, we derive a new schedule for the tool group every time a lot arrives in front of the tool group. If a batch formed by the time window approach is not full, then we try to increase the fullness of the batch by choosing lots among the waiting lots, but eventually unimportant lots of the same family.

COMPUTIONAL RESULTS

In this section, we present the results of simulation experiments with the suggested heuristics. The resulting performance measures are presented in terms of the ratio of the performance measure value of the heuristic and performance measure value obtained by using the SLACK dispatching rule.

Because we do not take future lot arrivals into account for SBDH, we have to consider only the first three factors from Table 2. We use the tupel (dispatching rule, level from factor 1, level fom factor 2, level from factor 3) in order to describe the used factor combination. Table 3 shows the results for the SBDH-based batching strategy for the 2 product-case, Table 4 for the 8 product-case, and Table 5 for the 16 product-case.

Table 3: Results for SBDH for Two Products

Factor Combination	TWT_{total}	CT	TP
SLACK (I-I-I)	1.0000	1.0000	1.0000
SBDH (I-I-I)	0.8409	1.0000	1.0032
SLACK (I-I-II)	1.0000	1.0000	1.0000
SBDH (I-I-II)	0.6312	1.0037	0.9988
SLACK (I-II-I)	1.0000	1.0000	1.0000
SBDH (I-II-I)	1.2190	0.9997	1.0002
SLACK (I-II-II)	1.0000	1.0000	1.0000
SBDH (I-II-II)	1.1052	0.9977	1.0029

Table 4: Results for SBDH for Eight Products

Factor Combination	TWT_{total}	CT	TP
SLACK (II-I-I)	1.0000	1.0000	1.0000
SBDH (II-I-I)	0.9885	1.0034	1.0063
SLACK (II-I-II)	1.0000	1.0000	1.0000
SBDH (II-I-II)	0.9850	0.9995	1.0033
SLACK (II-II-I)	1.0000	1.0000	1.0000
SBDH (II-II-I)	1.0378	1.0077	1.0044
SLACK (II-II-II)	1.0000	1.0000	1.0000
SBDH (II-II-II)	1.1227	1.0194	1.0042

Table 5: Results for SBDH for Sixteen Products

Factor Combination	TWT_{total}	CT	TP
SLACK (III-I-I)	1.0000	1.0000	1.0000
SBDH (III-I-I)	0.9895	1.0106	1.0000
SLACK (III-I-II)	1.0000	1.0000	1.0000
SBDH (III-I-II)	1.0385	0.9953	1.0143
SLACK (III-II-I)	1.0000	1.0000	1.0000
SBDH (III-II-I)	1.0113	0.9968	0.9966
SLACK (III-II-II)	1.0000	1.0000	1.0000
SBDH (III-II-II)	0.9769	1.0032	1.0062

From the experiments with SBDH, we can verify that the batching heuristic outperforms the slack rule only for the case of a homogenous product mix. In the inhomogeneous case, only a small number of lots of the second product exists. The SBDH-based batching strategy is a full-batch strategy, which leads to longer waiting times for lots belonging to families with less lots.

There is an even smaller improvement in the 8 product-case and the 16 product-case which confirms this thesis because the number of lots for a single product is even more smaller compared to the 2 product-case.

For the DBDH-based batching strategy the fourth experimental factor (time window size) is also important. The results for DBDH are shown in Table 6 and 7

Table 6: Results for DBDH for Two Products

Factor Combination	TWT_{total}	CT	TP
SLACK (I-I-I)	1.0000	1.0000	1.0000
DBDH (I-I-I-I)	1.1061	1.0033	0.9965
DBDH (I-I-I-II)	1.2252	1.0082	0.9974
SLACK (I-I-I)	1.0000	1.0000	1.0000
DBDH (I-I-II-I)	0.6994	1.0027	1.0002
DBDH (I-I-II-II)	0.7386	1.0039	0.9951
SLACK (I-II-I)	1.0000	1.0000	1.0000
DBDH (I-II-I-I)	0.8551	0.9920	1.0116
DBDH (I-II-I-II)	0.8582	0.9947	1.0004
SLACK (I-II-II)	1.0000	1.0000	1.0000
DBDH (I-II-II-I)	0.6748	0.9917	0.9994
DBDH (I-II-II-II)	0.5956	0.9869	1.0006

Table 7: Results for DBDH for Eight Products

Factor Combination	TWT_{total}	CT	TP
SLACK (II-I-I)	1.0000	1.0000	1.0000
DBDH (II-I-I-I)	0.9621	1.0091	0.9789
DBDH (II-I-I-II)	0.9307	1.0065	0.9753
SLACK (II-I-II)	1.0000	1.0000	1.0000
DBDH (II-I-II-I)	0.9052	0.9952	0.9957
DBDH (II-I-II-II)	0.8858	0.9839	0.9856
SLACK (II-II-I)	1.0000	1.0000	1.0000
DBDH (II-II-I-I)	1.1447	1.0266	0.9982
DBDH (II-II-I-II)	1.2222	1.0412	0.9991
SLACK (II-II-II)	1.0000	1.0000	1.0000
DBDH (II-II-II-I)	1.1568	1.0236	1.0029
DBDH (II-II-II-II)	1.2261	1.0425	0.9914

Both batching strategies, SBDH and DBDH, are sensitive to product mix and weight settings. It is interesting to see that in the 2 product-case the DBDH-based strategy outperforms the other batching strategies only for inhomogeneous product mixes. Considering future lot arrivals allows to decide whether it is advantageous to wait for the next incoming lot of a family with smaller number of lots or to start a non-full batch.

In the 8 product-case, the results are not the same as expected from the 2 product-case. The number of lots for a single product becomes so small for the inhomogeneous product mix that the waiting times for filling a batch are huge. Especially the minimum batch size ($B_{\min} = 2$) enforces this effect.

This becomes more clear when looking at the utilization data of the batching tool group. In Table 8, batch utilization (average number of lots that form a batch), tool group utilization and average queue size of the factor combinations II-I-I and II-II-I are shown.

Table 8: Utilization of the batching tool group OXIDE_1

Factor Combination	Batch Utilization	Utilization	Average Queue Size
SLACK (II-I-I)	1.0000	1.0000	1.0000
SBDH (II-I-I-)	1.0125	0.9931	0.9652
DBDH (II-I-I-I)	1.3451	0.6125	3.9745
DBDH (II-I-I-II)	1.2982	0.6153	4.5564
SLACK (II-II-I)	1.0000	1.0000	1.0000
SBDH (II-II-I)	0.9994	1.0036	0.9736
DBDH (II-II-I-I)	1.0070	0.8855	1.1583
DBDH (II-II-I-II)	1.0223	0.8262	1.3493

In the case II-I-I, considering future lot arrivals leads to a larger batch utilization and a larger queue size. The tools wait for lots which will arrive during a given time window. In the case II-II-I, the increment of those measures is less. This is caused by the effect that the starting non-full batches is a preferred decision.

The influence of the considered time horizon is pointed out in the results of the 16 product-case shown in Table 9. Especially in situations with a small number of lots per product, the arrival frequency of lots of the same product is very small. Therefore, it is reasonable to enlarge the time horizon for considering future lot arrivals in order to improve batching decisions.

Table 9: Results for DBDH for Sixteen Products

Factor Combination	TWT_{total}	CT	TP
SLACK (III-I-I)	1.0000	1.0000	1.0000
DBDH (III-I-I-I)	1.0079	1.0255	0.9860
DBDH (III-I-I-II)	0.9797	1.0207	0.9689
SLACK (III-I-II)	1.0000	1.0000	1.0000
DBDH (III-I-II-I)	1.0504	1.0186	0.9864
DBDH (III-I-II-II)	1.0196	1.0175	0.9726
SLACK (III-II-I)	1.0000	1.0000	1.0000
DBDH (III-II-I-I)	0.8407	0.9624	0.9342
DBDH (III-II-I-II)	0.8391	0.9566	0.9244
SLACK (III-II-II)	1.0000	1.0000	1.0000
DBDH (III-II-II-I)	0.7843	0.9141	0.9708
DBDH (III-II-II-II)	0.7619	0.8978	0.9589

SUMMARY

In this paper we evaluated two strategies for batching in a waferfab. We studied the influence of the number of products on the performance of two strategies that we suggested in (Mönch and Habenicht 2003).

The first strategy does not take any future lot arrivals into account. In contrast, we defined a certain time window in which future lot arrivals are considered for the second strategy. We presented results for a different number of products and different product mixes.

The results show that the number of lots in one family is a very important factor for the performance of the strategies. Hence, it is useful to assess the performance of batching strategies in case of product mix changes.

The performance of the two heuristics can be improved by determining more meaningful internal due dates and future lot arrival estimates. A finite capacity scheduling algorithm working on an aggregated model (cf Habenicht and Mönch 2002) may lead to more accurate lot arrival information and hence to a better batch decision-making.

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