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IMPACT OF QUALIFICATION MANAGEMENT ON SCHEDULING IN SEMICONDUCTOR MANUFACTURING

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ABSTRACT

A qualification management software that proposes recipe qualifications on tools in toolsets for semiconductor manufacturing has been developed. The qualification proposals are based on flexibility measures that have been shown to model capacity allocation in semiconductor workshops. In this paper, qualifications are used in order to see how increased flexibility for the capacity allocation improve scheduling. For this a scheduler simulator for the photolithography area has been used. Tests prove that qualifications – if they are well managed – both enable the simulator to achieve better scheduling and enable toolsets to be less sensitive to tool breakdowns.

1 INTRODUCTION

With a recipe in semiconductor manufacturing is meant instructions for a process type on a tool; how the tool should perform the process. In order to enable a tool to perform a process, the recipe of the process needs to be qualified. However, since it requires effort, and in the end costs money, to qualify and maintain recipes on tools and because it is not possible to qualify some recipe on some tools, all recipes are not qualified on all tools. This could prevent the tools to be used optimally. Our hypothesis is that, through good qualification management (QM) of recipes, tools can be more efficiently used. We believe that this can be achieved by conducting recipe qualification such that there is a great flexibility for the capacity allocation so that the WIP (work-in-progress) for the processes can be well balanced on the tools and the production is robust when a tool becomes unavailable (in case of maintenance or break down).

In this article we are interested in evaluating the impact of recipe qualifications of tools on scheduling performances. For this a qualification management software has been developed. This software enables to see which recipes are currently qualified on the tools in a workshop in a wafer fab. The software also proposes additional qualifications that will increase the flexibility of a toolset. Using the software, different qualification sets have been tested with a scheduling simulator for the photolithography area. From the tests it will be seen that flexible capacity allocation can improve cycle times, tool charge and robustness for scheduling.

1.1 Scheduling

Scheduling is one of the most studied operations research problems. However, to include all details may lead to very complex simulation models (Artigues et al. 2006). In this paper a scheduling simulator described by Yugma et al. (2007) is used. It is a scheduling simulator for the photolithography workshop. The simulator has been developed based on some simple principles (Vialletelle and France 2006); by first sorting the lots based on their priorities and thereafter dispatching them one by one on the tools to obtain a fully scheduled workshop.

1.2 Qualification Management

Although much has been written about scheduling only little has been written on Qualification Management (QM) for semiconductor manufacturing. Some articles describe programs that display the current recipe-tool statuses in the fab (Yurtsever and Comerford 1995, Pierce and Yurtsever 1999). The programs, however, do not propose any changes of the current settings.

Otherwise QM has been used for fault detection control (FDC). In (Ono et al. 2003) recipe evaluation in correlation with defect distribution on wafers are studied. Furthermore, Zahara and Fan (2003) present a system where recipes are modified at each run at the CMP workshop (Chemical Mechanical Polishing).

Williams (1999) describes the requirements for recipe management and that it can improve the efficiency of the fab. This can be obtained by supplying schedulers and dispatchers with recipe availability and characteristic of the fab tools. In spite of this he is not suggesting any preventive measures for recipe qualification that could improve the effectiveness of the fab.

Interestingly, Ignizio (2006) mentions how QM could be used in order to decrease the reentrancy in the fab. He presents a measure of the degree of reentrancy but no study on what effect this might have on the fab performance has been published.

In fact, Johnzén et al. (2007) recognize that efficient QM may help dispatchers and schedulers to achieve more flexible workshops. It is also stressed that uncertainties such as tool breakdowns should be considered to obtain robust QM.

This is the starting point from which this paper has been initiated. To our knowledge no such study has been performed before.

We will start describing the QM software that suggests recipe qualifications on tools which will increase the flexibility of the capacity allocation in a workshop. Thereafter flexibility measures are recalled from previous work (Johnzén et al. 2007, Johnzén et al. 2008). We also recall the concepts of the scheduling simulator that has been used for the tests (Yugma et al. 2007). Thereafter we describe the tests that have been conducted. The impact of these tests are analyzed in the perspective of qualifications, flexibility and robustness. Lastly we will conclude the tests and the analysis.

2 A QUALIFICATION SOFTWARE

A qualification software for front-end production has been developed. The software display the current qualifications and suggests additional qualifications that increase the flexibility for capacity allocation. The flexibility is measured as described by Johnzén et al. (2007). Furthermore, Johnzén et al. (2008) presented some alternative flexibility measures that were compared with the former. It was proved that these flexibility measures model capacity allocation for qualification management.

The four best flexibility measures are:

- WIP flexibility,
- Time flexibility,
- Toolset flexibility,
- And System flexibility.

Each of the measures considers on which tools in a workshop the recipes are qualified and how large is the WIP quantity that awaits to be processed for each recipe. The measures regard different aspects of flexibility, and enables to compare different qualification sets for workshops in order to see which would be the most favorable qualification setting for the workshop. The measures are weighted such that their values lies between 0 and 1. To improve the visibility for the operators in the production it has been decided to translate the values to percentages between 0 and 100.

2.1 Notations

The parameters that have been used for the definition of the flexibility measures are the following:

- NB_{tools} – Number of tools in the toolset.
- NQT_r – Number of qualified tools for recipe r.
- WIP_r – WIP quantity for recipe r.
- γ – Flexibility balance exponent (> 1).

Additionally, the measures contain the following variables, which are decided from optimization procedures:

- $WIP(t)$ – Total WIP quantity assigned to tool t.
- $C(t)$ – Total production time assigned to tool t.
- C_{ideal} – The optimal value of $\sum_{\forall t} C(t)^{\gamma}$ when all recipes are qualified

2.2 WIP Flexibility

The capacity allocation of a workshop is considered to be flexible if it is possible to distribute the WIP quantities of the recipes such that there can be a well-balanced workload on the tools. The WIP flexibility measure (1) considers how good the WIP quantities can be balanced on the tools. In order to use the measure, an optimal WIP balance needs to be found (Johnzén et al. 2008).

$$F^{WIP} = \frac{NB_{tools} \times (\sum_{\forall t}(WIP(t))/NB_{tools})^{\gamma}}{\sum_{\forall t} WIP(t)^{\gamma}} \in (0,1] \quad (1)$$

2.3 Time Flexibility

The time flexibility measure (2) works similarly as the WIP flexibility measure. But instead of considering the direct balance of the WIP quantities on the tools, the throughput times (*the time to process a wafer*) are considered. Since the throughput times are variable it is both needed to balance the throughput times on the tools and to minimize the overall throughput time.

$$F^{time} = \frac{C_{ideal}}{\sum_{\forall t} C(t)^{\gamma}} \in (0,1] \quad (2)$$

2.4 Toolset Flexibility

While the WIP flexibility and time flexibility assures the workload to be well-balanced on the tools in a workshop, it is not sure that production can be continued without problems if a tool is unavailable for a certain period of time (due to e.g. maintenance or breakdown). It needs to be assured that the WIP quantities of the recipes can be processed on alternative tools if one gets unavailable. The toolset flexibility (3) considers both the WIP quantities and how many tools that are already qualified for the recipes. The higher WIP quantity for a recipe, the more important it becomes to make an additional qualification for the recipe. However, if many tools already have been qualified for a recipe, an additional qualification is considered to be less important.

$$F^{TS} = \frac{WIP_{total}}{N_t \times \sum_{\forall r} (WIP_r / NQT_r)} \in (0,1] \qquad (3)$$

2.5 System Flexibility

The system flexibility (4) considers all of the three previously mentioned flexibility measures. By setting the parameters a, b and c to different values, it is possible to choose the importance of each flexibility measure. The values of a, b and c are chosen such that their sum equal 1 and such that they are greater than 0.

$$F^{SYS} = a \times F_{WIP} + b \times F_{time} + c \times F_{TS} \in (0,1] \qquad (4)$$

3 SCHEDULING SIMULATOR

Yugma et al. (2007) describe a scheduling simulator for a photolithography workshop. The simulator first sorts the lots using their priorities and their day-at-operation (DAO). Lots with high priority, so called hot lots, should be processed before low priority lots. Thereafter the lots are chosen in this order and placed one by one on the tools in the photolithography area within a certain time limit α. To which tool a lot is dispatched depends on four local rules:

- c1 Tool availability,
- c2 Tool charge,
- c3 Mask location,
- c4 Batch configuration.

The *tool availability* rule lets a lot be assigned to a tool if it can be scheduled within a certain time limit α. If not, it will, if possible, be dispatched on another tool, or else it will be scheduled in another period. For the *tool charge* rule, the simulator tries to schedule the lots such that the workload on each tool will be even. It can be chosen if the tool charge should consider the number of lots per tool or WIP quantity per tool as workload. For the *mask location* rule, it is considered favorable if the mask is already on the tool where it should be processed. Similarly, for the *batch configuration* rule, it is considered to be good if the configurations do not need to be changed on the tool for the lot. Preferably a lot should have the same batch configuration as the previous lot processed on the tool

When no more lots can be scheduled within a period $(0,\alpha)$, the remaining lots are sorted again and thereafter scheduled at the next period $(\alpha, 2\alpha)$ and so on.

4 IMPACT OF QUALIFICATION MANAGEMENT ON SCHEDULING

In order to see the impact of qualifications, it has been decided to test different qualification sets on the scheduling simulator described in the previous section. Input data for the tests have been obtained from the STMicroelectronics 300mm front-end wafer fab. The tests have been performed for a toolset with six tools and lots with different WIP quantities. The throughput times have been randomly generated (evenly distributed between 40 and 100 s/wafer), such that they are the same for the first (A), the second (B) and the sixth (F) tools. Also, the throughput times for Tool 4 (D) are the same as for Tool 5 (E), whereas the throughput times for Tool 3 (C) are independent from the other tools. It is considered that all recipes can be qualified on all tools. The batch configuration setup is set to five minutes. The setup of a new mask on a tool takes one minute. For all tests using the WIP flexibility measure or the time flexibility measure γ has been given the value 2.

4.1 Performance Measures

The performance measures that have been used for the tests are:

- DAO – Day-at-operation - how many hours in average the lots stay in the workshop.
- σDAO – the standard deviation of the DAO.
- 8th decile DAO – the DAO for the lot where 80 percent of the lots have lower DAO.
- Max tool charge – the WIP quantity for the tool with the highest WIP quantity.

Since fab managers want to avoid that lots stay too long in the fab, it is important to decrease the average DAO of the lots. The standard deviation of the DAO and the 8th decile of the DAO indicate the variability of the cycle time of the lots. The max tool charge indicates if the lots can be well spread on the tools. A high max tool charge indicates that it might take long time to process all the lots.

Note that all qualifications increase the toolset flexibility measure (and therefore also the system flexibility) but not necessarily the WIP flexibility measure or the time flexibility measure. The different flexibility types will be analyzed separately in the sequel.

4.2 WIP Flexibility Qualifications

In this first series of tests, qualifications that optimize the WIP flexibility have been chosen. The results of the qualifications can be seen in Table 1.

Table 1: Qualifications based on WIP flexibility.

Nb of qualifications	0	1	2	3	4
F^{WIP} (%)	67	82	99	100	100
F^{time} (%)	63	76	84	85	95
F^{TS} (%)	22	24	25	30	34
DAO	5.5	5.2	5.0	4.8	4.8
σDAO	3.2	3.4	3.5	3.6	3.6
DAO 8th decile	6.0	5.6	5.0	4.6	4.9
Max tool charge	300	229	207	200	207

Since a toolset with high WIP flexibility allows the WIP to be well spread on the tools, it seems logical that the max tool charge values can stay quite low which is confirmed by the tests. The tests with increasing WIP flexibility shows that the max tool charge and the DAO values decreases quite much until the WIP flexibility gets close to 100 percent. When the WIP flexibility gets close to 100 percent it becomes hard to improve the tool charge, and other factors interfere with the results. For example, the batch configuration rule or the tool availability rule might affect the results.

4.3 Time Flexibility Qualifications

Starting from the same qualifications as in the previous example, qualifications based on the time flexibility measure has been conducted (results in Table 2).

Table 2: Qualifications based on time flexibility.

Nb of qualifications	0	1	2	3	4
F^{WIP}(%)	67	78	89	95	100
F^{time}(%)	63	76	88	93	96
F^{TS} (%)	22	23	24	28	31
DAO	5.5	5.1	5.0	4.9	4.8
σDAO	3.2	3.4	3.5	3.5	3.6
DAO 8th decile	6.0	5.6	5.0	5.1	4.8
Max tool charge	300	300	250	275	206

The qualifications based on time flexibility indicates similar tendencies as the WIP flexibility. Also for the time flexibility, the DAO and tool charge decrease quite much in the beginning until the time flexibility gets close to 100 percent.

4.4 WIP Flexibility versus Time Flexibility

This is hard to see major differences between the results from the test series based on WIP flexibility and time flexibility. Hence some special cases have been searched where WIP flexibility was close or equal to 100 percent, and where time flexibility was either quite low (qualifications are made on slow tools) or as well close or equal to 100 percent. The average of different cases with 16 to 18 qualifications for 12 recipes on six tools are compared in Table 3.

Table 3: Comparing WIP flexibility with time flexibility.

Flexibility	WIP	WIP+time
F^{WIP}(%)	100	100
F^{time}(%)	55	100
F^{TS}(%)	25	27
DAO	4.7	4.9
σDAO	3.5	3.5
DAO 8th decile	5.0	5.3
Max tool charge	205	216

The tests for the time flexibility do not indicate any greater differences with the WIP for the scheduling other than those observed for the WIP flexibility. In some of the tests the results are better for the WIP flexibility and some for the time flexibility. This might due to the fact that there is no rule in the simulator favoring lots to be processed on tools with faster throughput times. Hence the effect from the time flexibility measure does not result in any additional effect compared to the WIP flexibility measure. It has thus been suggested that the tool charge rule in the simulator should be based on throughput times.

4.5 Toolset and System Flexibility Qualifications

The toolset flexibility measure indicates which recipe needs more capacity and not on which tool a qualification should be conducted. Therefore different possibilities for qualification strategies for the tools are possible. Table 4 shows qualifications on randomly chosen tools for recipes that will increase the toolset flexibility the most. In Table 5, the same recipes have been qualified. However, these recipes are qualified on the tools which will increase the system flexibility the most.

The tests have indicated that qualifications only based on toolset flexibility do not necessarily improve the performance if they do not also increase the WIP flexibility or the time flexibility (deducted from the system flexibility). However, increased toolset flexibility should increase the robustness of the workshop.

Table 4: Qualifications based on toolset flexibility and system flexibility. ($a = 0.1$, $b = 0.1$, $c = 0.8$)

Nb of qualifications	0	1	2	3	4
F^{WIP}(%)	67	67	68	68	68
F^{time}(%)	63	63	63	63	63
F^{TS} (%)	22	25	28	31	34
F^{SYS} (%)	30	33	35	38	40
DAO	5.5	5.5	5.6	5.2	5.1
σDAO	3.2	3.2	3.3	3.5	3.5
DAO 8th decile	6.0	6.0	6.0	5.7	5.5
Max tool charge	300	300	251	232	223

Table 5: Qualifications based only based on toolset flexibility. ($a = 0.1$, $b = 0.1$, $c = 0.8$)

Qualifications	None	1	2	3	4
F^{WIP} (%)	67	76	96	98	100
F^{time} (%)	63	69	74	79	95
F^{TS} (%)	22	25	28	31	34
F^{SYS} (%)	30	35	39	43	47
DAO	5.5	5.2	4.8	4.8	4.8
σDAO	3.2	3.4	3.6	3.6	3.6
DAO 8th decile	6.0	5.9	5.8	4.9	4.9
Max tool charge	300	300	250	228	182

4.6 Tool Availability

To see what kind of qualification policies minimize the effects when tools are unavailable (e.g. breakdowns or maintenance), tests have been performed with scenarios where different tools are simulated as being unavailable one by one. In Table 6, it can be seen what happens if each of the tools becomes unavailable separately.

In most of the cases, no major difference occur; the DAO and the tool charge rise a little. However if tool D becomes unavailable, three lots cannot be dispatched, and if tool F breaks down, nine lots cannot be dispatched. Out of these nine lots, three are so called hot lots (high priority lots). In fact many of the recipes qualified on tool F are not qualified on other tools. Although it initially looks like the system can be well balanced, if tool F becomes unavailable, it may have serious effects, especially since many hot lots would be affected.

If the tool unavailabilities would have been considered beforehand, the question is: could qualifications based on the flexibility measures have reduced the effects? In Table 7, the flexibility measures for different qualifications are shown. For the system flexibility, a and b are both set to 0.1, whereas the toolset flexibility parameter is set to 0.8

Table 7: Qualification proposals from the flexibility measures

Flexibility measure	Previous value	New value	Qualification of **recipe** on *tool*	
F^{WIP} (%)	94	97	**6**	*F*
F^{time} (%)	67	70	**6**	*F*
F^{TS} (%)	34	38	**11**	*A, B, C, D, E*
F^{SYS} (%)	43	46	**11**	*A*

The WIP flexibility and time flexibility recommend to qualify Recipe 6 on Tool F – since not a so large WIP quantity could be placed on Tool F. The toolset flexibility recommends to qualify Recipe 11 – which is currently only qualified on Tool F – on any other tool (A, B, C, D or E). The system flexibility recommends qualification of Recipe 11 on Tool A. In tables 8, 9 and 10 the same test as in Table 6 is performed for unavailable tools in the workshop, but with the proposed qualifications. For Table 8, Recipe 6 has been qualified on tool F as proposed by the WIP flexibility and time flexibility measures. In Table 9, it has been chosen to qualify Recipe 11 on Tool B which was one of the tools recommended by the toolset flexibility measure. Finally, in Table 10, Recipe 11 is qualified on Tool A as recommended by the system flexibility measure.

Surprisingly, the results do not show any major changes when comparing the different cases, except for the case when tool F is unavailable, which the toolset flexibility and the system flexibility measures handle much better. In this case, it becomes possible to process 70 of the 74 lots and 6 of the 7 hot lots. On the contrary, the qualification proposed by the WIP flexibility and time flexibility measures does not improve the situation when tool F is down.

Workshops which have just a few qualifications for some of the recipes can still have quite high WIP flexibility or time flexibility. However, such workshops will be quite vulnerable when tools are unavailable for processing. On the opposite, the toolset flexibility tends to favor qualifications for recipes which currently only has few qualified tools. Such qualifications will make the capacity allocation more robust and the toolset less sensitive for tool breakdowns.

For the tests in this section, the qualifications proposed by the toolset flexibility and the system flexibility enable two additional hot lots to be processed. However, the flexibility measures do not consider the lot priorities, and this may not always be the case. However, the tests show that more lots can be processed in a workshop with a larger toolset flexibility measure.

Table 6: Scenarios with unavailable tools.

Tool unavailable	0	A	B	C	D	E	F
Nb of dispatched lots	74	74	74	71	74	74	65
Nb of dispatched hot lots	7	7	7	7	7	7	4
DAO	22.5	23.2	22.9	24.1	22.8	22.9	25.6
σDAO	29.8	29.6	29.7	29.6	29.8	29.7	32.5
DAO 8th decile	29.8	29.8	30.9	34.2	31.3	30.7	35.1
Max tool charge	294	374	389	388	414	440	300

Table 8: Recipe 6 has been qualified on tool F as recommended by the WIP flexibility measure. The table shows what would happen if each tool becomes unavailable.

Tool unavailable	0	A	B	C	D	E	F
Nb of dispatched lots	74	74	74	71	74	74	65
Nb of dispatched hot lots	7	7	7	7	7	7	4
DAO	22.3	23.0	22.8	23.8	22.6	22.7	25.6
σDAO	29.8	29.6	29.7	29.7	29.8	29.7	32.5
DAO 8th decile	29.8	29.8	30.8	33.2	31.0	30.5	35.1
Max tool charge	292	360	376	383	405	420	300

Table 9: Recipe 11 has been qualified on tool B as recommended by the toolset flexibility measure. The table shows what would happen if each tool becomes unavailable.

Tool unavailable	0	A	B	C	D	E	F
Nb of dispatched lots	74	74	74	71	74	74	70
Nb of dispatched hot lots	7	7	7	7	7	7	6
DAO	22.4	23.1	22.9	24.0	22.8	22.8	24.0
σDAO	29.9	29.7	29.7	29.6	29.8	29.8	32.1
DAO 8th decile	29.7	29.9	30.9	33.8	31.2	30.6	31.4
Max tool charge	292	360	376	383	405	420	300

5 CONCLUSIONS AND PERSPECTIVES

It has been shown that performing just a few additional qualifications may improve the conditions for scheduling. This is possible when recipes are qualified on tools that increase the flexibility of the capacity allocation.

We have seen how tool charge, DAO and other performance measures may be improved until the WIP flexibility or time flexibility measures are close to 100 percent. Thereafter improvements are difficult and qualifications might even worsen the performance measures a little. This might happen when the scheduler simulator tries to compensate for the different local rules.

A workshop with high toolset flexibility does not necessarily increase the performance of the workshop. It was, however, shown that, even when the time flexibility or WIP flexibility measures are close to 100 percent, increasing the toolset flexibility may improve the robustness of a workshop when tools become unavailable.

It should be noted that the Qualification Management software does not explicitly consider detailed scheduling considerations such as batch configurations, mask trains and lot priorities. This may significantly influence the scheduling in some cases. A goal is to study whether and how these elements should be included when proposing new optimal qualifications.

Different models on how several qualifications can be conducted optimally have been developed. They should be tested, to see which of these methods is the most suitable. A relevant method should both provide sufficiently good solutions with reasonable computing times.

Table 10: Recipe 11 has been qualified on tool A as recommended by the system flexibility measure. The table shows what would happen if each tool becomes unavailable.

Tool unavailable	0	A	B	C	D	E	F
Nb of dispatched lots	74	74	74	72	74	74	70
Nb of dispatched hot lots	7	7	7	7	7	7	6
DAO	22.4	23.2	22.9	23.5	22.7	22.9	24.0
σDAO	29.8	29.6	29.7	30.0	29.8	29.8	32.1
DAO 8th decile	29.7	29.8	30.8	32.3	32.2	30.6	30.7
Max tool charge	294	374	380	368	411	429	341

Additional features, not discussed in this paper, have been implemented in the Qualification Management software. However, additional tests are necessary before fully deploying these features. For instance, it is possible to group qualifications in different easiness levels. This is because some qualifications take shorter time than others and are considered to be easier to conduct.

We also aim at continuing further tests with scheduling in other areas of the fab to verify whether the results are similar. A simulator for the etch area similar to the one of photolithography is under development, based on rules that are somewhat different.

Also, it may be relevant to adjust the scheduler simulator for photolithography. Our tests have indicated that the scheduling rules play an important role in the results. In particular, the trade-off between the batch configuration rule and the tool charge rule should be tested. It should also be considered if process times should be considered by the tool charge rule.

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