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FLEXIBILITY MODELS FOR CAPACITY ALLOCATION IN SEMICONDUCTOR FABRICATION

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ABSTRACT: *In order to increase the flexibility for capacity allocation in semiconductor fabs, three measures have been developed (Johnzén et al 2007a); flexibility measures for toolset, WIP (Work-In-Progress) and system. These measures have been developed to support process qualification in semiconductor fabs, where processes need to be qualified before they can be performed on tools. In this paper a new flexibility measure that considers the tools production times is presented: the time flexibility measure. The measures are motivated, and alternative measures are defined. Examples show how the measures model the flexibility of the qualification management for capacity allocation. In addition the original and alternative measures are compared in order to see which are the most effective. Furthermore numerical experiments are conducted, which show the results of qualifications and parameter adjustments using the flexibility measures.*

KEYWORDS: *Distribution models, capacity allocation, qualification management, flexibility*

1. INTRODUCTION

The settings to perform a process on a tool in a semiconductor fab (fabrication plants) are called a recipe; and before a process can be performed the corresponding recipe needs to be qualified on the tool (Williams 1999), (Achacoso and Pispia 1995). However, since the qualifications of recipes are associated with maintenance, costs and need of manpower, only a sufficiently small number of the recipes are qualified (Johnzén et al 2007b). Especially in high-mix/low-volume semiconductor fabs (Mahoney 1997), where products change rapidly, operators must have flexibility to choose where to process their products. In order to support the decisions on which tools the recipes need to be qualified at, measures of flexibility have been developed (Johnzén et al 2007a), each based on the following criteria:

1. *Toolset flexibility* - The possibility to perform processes with high WIP quantities on as many tools as possible.
2. *WIP flexibility* - The possibility to balance the total workload on the tools in a toolset.
3. *System Flexibility* - Considers the effects from both of the previous criteria.

In this paper, we present these measures and motivate their formulations. We also present and motivate a new measure: the time flexibility. Some alternative formulations of the original measures are presented. In order to see how the measures model the flexibility for capacity allocation, examples are shown. Thereafter we compare the measures in order to see whether the original or the alternative formulations should be used. We furthermore present numerical experiments that have been performed, which show how well the measures actually model the flexibility. Finally conclusions are drawn and perspectives for further studies are discussed.

2. FLEXIBILITY MEASURES

Although flexibility has been the subject of study in many papers (Browne 1984) and (Sethi and Sethi 1990), not so many models for measuring flexibility have been developed (De Toni and Tonchia 1998). A few researchers such as (Das 1996) and (Rossi 2003) have developed measures, but these are not considered to be applied for capacity allocation. To our knowledge no flexibility measures have been developed to improve qualification management (QM) and capacity allocation for semiconductor fabs.

2.1. Original flexibility measures

Three flexibility measures have been developed (Johnzén et al 2007a). Their values lie between 0 and 1, where 1 denotes maximum flexibility. In order to increase visibility for the operators in the fab, the values are expressed as percentages between 0 and 100%.

2.1.1 Notations

The following parameters are necessary for the definition of the flexibility measures.

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 contains variables, which are decided from optimization procedures (see Sections 2.1.3, 2.2.1, 2.3.2 and 5 for more information).

$WIP(t)$	Total WIP quantity assigned to tool t.
$C(t)$	Total production time assigned to tool t.

2.1.2 Toolset flexibility

The toolset flexibility measure (1) stresses the importance of having many qualified tools for recipes with high WIP quantities. This is done by multiplying the variable NQT_r with the WIP quantity of the same recipe r; in this way qualifications on tools for recipes with high WIP quantities will be valued more.

$$F^{TS} = \frac{\sum_r (NQT_r \times WIP_r)}{NB_{tools} \times \sum_r WIP_r} \qquad (1)$$

If all tools would be qualified for all recipes, then NQT_r would equal NB_{tools} for all recipes. Thus the sum in the numerator would equal the product in the denominator and $F^{TS} = 1$.

2.1.3 WIP flexibility

The WIP flexibility measure (2) evaluates how good the WIP quantities can be balanced on a set of tools. The WIP flexibility measure increases when $\sum_{\forall t} WIP(t)^{\gamma}$ decreases; the total WIP quantity is constant, but as the WIP becomes more balanced, the sum in the denominator decreases. By increasing the parameter γ, the value of the WIP flexibility changes, but a better balanced WIP would still measure a higher WIP flexibility than a worse balanced.

$$F^{WIP} = \frac{NB_{tools} \times \left(\sum_t (WIP(t)) / NB_{tools}\right)^{\gamma}}{\sum_t WIP(t)^{\gamma}} \qquad (2)$$

If the WIP can be perfectly balanced on all tools, then $WIP(t) = \sum_t (WIP(t))/NB_{tools}$ for all tools. Thus the sum in the denominator will equal the product in the numerator and $F^{WIP} = 1$. However, in order to use the WIP flexibility measure, *the optimal balance of the WIP quantities on the tools need to be determined*. To do that, **it is required to solve an optimization problem** (see Section 5).

2.1.4 System flexibility

In order to model the effects from both the toolset flexibility and the WIP flexibility a new measure was defined. For the system flexibility measure (3), the toolset flexibility measure (1) is combined with the WIP flexibility measure (2). This is done by multiplying the toolset flexibility measure with the WIP flexibility measure.

$$F^{SYS} = F^{TS} \times F^{WIP} \qquad (3)$$

When both the toolset flexibility measure and the WIP flexibility measure equal 1, then the system flexibility measure will also equal 1. This will only occur when all recipes are qualified on all tools.

2.2. Additional flexibility measures

Additionally to the three original flexibility measures presented in (Johnzén et al 2007a), a time flexibility measure has been developed. This can be seen as an extension of the WIP flexibility measure where, instead of WIP quantities, production times on the tools are considered.

2.2.1 Time flexibility

From the WIP flexibility measure (2) the total WIP quantity $\sum_t WIP(t)$ and the WIP quantities per tool $WIP(t)$ have been exchanged with the total production time $\sum_t C(t)$ and the production time per tool $C(t)$. The time flexibility measure is defined in 4. However, contrary to the WIP flexibility measure, the time flexibility measure (4) depends both on how the production times are well-balanced on the tools and how the total production time is minimized. This is due to that whereas the total WIP quantity $\sum_t WIP(t)$ is constant, the total production time $\sum_t C(t)$ is variable. As with the WIP flexibility, **it is required to solve an optimization problem** to find the optimal WIP balance for the time flexibility measure (see section 5). Through the flexibility balance exponent γ, it is possible to choose whether minimization or balancing should be most important (see Section 6.2).

$$F^{time} = \frac{NB_{tools} \times \left(\sum_t (C(t)) / NB_{tools}\right)^{\gamma}}{\sum_t C(t)^{\gamma}} \qquad (4)$$

Since the time flexibility measure works similarly as the WIP flexibility measure, it is possible to replace F^{WIP} with F^{time} for the system flexibility measure in expression (3).

2.3. Alternative flexibility measures

When validating the measures with practical instances, it has been thought of considering some additional characteristics for the measures. Hence, in addition to the definitions of the original flexibilities measures, some alternative measures have been derived.

2.3.1 Alternative toolset flexibility measure

An alternative formulation of the toolset flexibility measure has been defined (5). This alternative formulation has been developed since it is important to also take into account how many tools are already qualified for the recipes. When a new qualification is considered, the original measure will always propose a qualification for the recipe with the highest WIP quantity. For the alternative formulation, it is also considered important how many tools are already qualified for the recipe. An example of this is shown in Section 4.1.

$$F_{alt}^{TS} = \frac{\sum_r WIP_r}{NB_{tools} \times \sum_{\forall r} (WIP_r / NQT_r)} \tag{5}$$

If all tools are qualified on all recipes, then $NQT_r = NB_{tools}$, and thus the sum over all recipes will equal $\sum_r WIP_r / NB_{tools}$ and the alternative toolset flexibility is equal to 1.

2.3.2 Alternative time flexibility measure

One of the ideas of the time flexibility measure (4) was that production times should be minimized to gain flexibility. This is however being contradicted: Since the total production time $\sum_t C(t)$ is variable, the total production time may be increased when the time flexibility measure (4) is being maximized. To avoid this effect, an alternative version of the time flexibility measure with a constant value has been proposed (6). As with the WIP flexibility measure, the variable is kept in the denominator and for the numerator a normed term is defined. The new constant C_{ideal} is the maximum value of the sum of $C(t)^\gamma$ when all tools that can be qualified for the recipes are qualified; The ideal value of the denominator $\sum_{\forall t} C(t)^\gamma$ in 4. The alternative time flexibility measure (6) is therefore equal to 1 if all recipes are qualified. Again **it is required to solve an optimization problem** *to find the optimal balance for* $C(t)$.

$$F_{alt}^{time} = \frac{C_{ideal}}{\sum_{\forall t} C(t)^\gamma} \tag{6}$$

The alternative time flexibility measure will have high values both when the production times are well-balanced and when they are minimized.

2.3.3 Alternative system flexibility measure

In the original formulation of the system flexibility measure (3), it is not possible to increase the importance for one single component (F^{TS} and $F\ WIP$ or F^{TS} and F^{time} - see Section 2.2.1). Instead an alternative version of the system flexibility measure has been proposed where components are added with a parameter associated to each component (7). It is then possible to let one of the flexibility measures to be more influent by increasing the value of the parameters a, b or c, and to exclude one measure by setting the corresponding parameter to 0.

$$F_{alt}^{SYS} = a \cdot F^{TS} + b \cdot F^{WIP} + c \cdot F^{time} \tag{7}$$

In (7) the parameters – all between 0 and 1 – are defined such that $a+b+c \equiv 1$. This ensures that the alternative system flexibility measure only achieves values between 0 and 1. In (7) either the original or the alternative measures of F^{TS} and F^{time} may be used depending on what the users prefer.

3. EXAMPLES

In order to better understand how the flexibility measures function, examples of recipes with WIP qualified on tools in a toolset are explained with a purposed well-balanced capacity allocation. Since the time flexibility measure needs to have throughput times in order to be collected, examples for toolset, WIP and system flexibility (with $c = 0$ to exclude the time flexibility) measures are first shown in Section 3.1. In Section 3.2, throughput times are introduced for an example of the time flexibility measure.

3.1. Examples: flexibility measures

Consider the example in Table 1; three recipes (1, 2 and 3) with WIP quantities (50, 400, 450) await to be processed at a workshop with three tools (A, B and C). Recipe 1 and recipe 3 are qualified on tool B and tool C, while recipe 2 is only qualified on tool A. Furthermore, the WIP quantities are optimally distributed on the tools.

	Tool			
Recipe	A	B	C	WIP
1	-	25	25	50
2	400	-	?	400
3	?	225	225	450
Balance	400	250	250	900

Table 1. A workshop with WIP quantities from three recipes qualified and distributed on three tools

For the current qualifications, the flexibility measures are:

F^{TS} (F^{TS}_{alt})	0.52 (0.46)
F^{WIP}	0.95
F^{SYS} (F^{SYS}_{alt})	0.49 (0.74)

The WIP flexibility measure uses $\gamma = 2$. For both the original and alternative system flexibility measures, the original toolset flexibility is used. Additionally, for the alternative system flexibility measure, the parameters have been set as follows: $a = 0.5$, $b = 0.5$, $c = 0$. The question marks – ? – show possible new qualifications.

	Tool			
Recipe	A	B	C	WIP
1	-	25	25	50
2	300	-	**100**	400
3	?	275	175	450
Balance	300	300	300	900

Table 2. Recipe 2 qualified on tool C

By qualifying recipe 2 on tool C, the situation in Table 2 occurs. Note that the WIP quantities have been optimally rebalanced and the flexibility measures get new values:

F^{TS} (F^{TS}_{alt})	0.67 (0.67)
F^{WIP}	1.00
F^{SYS} (F^{SYS}_{alt})	0.67 (0.84)

If instead recipe 3 is qualified on tool A (Table 3), the optimal balance of WIP quantities remains the same as in Table 1.

	Tool			
Recipe	A	B	C	WIP
1	-	25	25	50
2	400	-	-	400
3	**0**	225	225	450
Balance	300	300	300	900

Table 3. Recipe 3 qualified on tool A

The flexibility measures become:

F^{TS} (F^{TS}_{alt})	0.69 (0.52)
F^{WIP}	0.95
F^{SYS} (F^{SYS}_{alt})	0.66 (0.82)

By only considering the original toolset flexibility measure, the qualification conducted in Table 3 would be the optimal one. However, the qualification conducted in Table 2 is favored by the alternative toolset flexibility measure and the WIP flexibility measure. Also the system flexibility measure favors the qualification in Table 2.

3.2. Example: time flexibility measure

If the throughput times of Table 4 are considered, the time flexibility measure can be calculated for the qualifications in Table 1.

	Tool		
Recipe	A	B	C
1	-	100	125
2	50	-	100
3	75	100	125

Table 4. Throughput times expressed as WIP quantity that can be processed per hour

With the production times being optimally balanced, the flexibility measures (with $\gamma = 2$) are:

F^{time} (F^{time}_{alt}) 0.93 (0.43)

To calculate these measures, it is required to find the WIP distributions which optimally balance and minimize the production times for both of the time flexibility measures respectively.

4. COMPARING MEASURES

In order to see whether the original or the alternative flexibility measures better model good flexibility for capacity allocation and qualification management, the measures are compared with each other.

4.1. Comparing the toolset flexibility

The question is whether the original toolset flexibility measure (1) or the alternative toolset flexibility measure (5) better models the capacity allocation. It can be answered using an example with two recipes and 10 tools. Recipe 1, with a WIP quantity of 1000, is qualified on one tool. Furthermore, recipe 2, with a WIP quantity of 1001, is qualified on nine tools. If conducting an additional qualification is considered, the original toolset flexibility would recommend qualifying the last unqualified tool for recipe 2, since only the recipe with the highest WIP quantity is considered as long as more qualifications can be conducted on this tool. However, recipe 1 clearly needs the additional capacity more, since the WIP quantities are almost the same for recipes 1 and 2, and recipe 1 has only one qualified tool whereas nine tools are qualified for recipe 2. Hence, another tool for recipe 1 should be qualified. The alternative toolset flexibility measure favors a qualification for recipe 1, and thus the alternative measure better models where qualification should be done for optimal capacity allocation.

4.2. Comparing the time flexibility

Two different strategies for distributing the WIP quantities are considered; one which aims at balancing the process times on the tools and one which aims both at minimizing and balancing the production times. The two strategies lead to the two solutions displayed in Table 5, where the two time flexibility measures are calculated with $\gamma = 2$. Considering the production times in this table, the second strategy is preferable since the total production time is smaller.

	Tool A	Tool B	F^{time}	F^{time}_{alt}
Strategy 1	10 h	10 h	0.67	0.51
Strategy 2	10 h	1 h	0.59	1.00

Table 5. Production times for a set of tools, using two different strategies

Since strategy 2 is considered preferable, the lower value of the original time flexibility measure for strategy 2 contradicts what is expected. On the contrary, with the value of the alternative time flexibility measure (with $C^{alltools}_{qualified} = 10^2 + 1^2 = 101$) is higher; a result which better measures what is expected. Hence, the alternative time flexibility measure is more suitable.

4.3. Comparing the system flexibility

The main difference between the original system flexibility measure and the alternative measure is that, with the alternative version, it is possible to regulate how much influence the different flexibility measures will have on the system flexibility measure. With the original system flexibility measure, no such regulation is possible.

5. BALANCING

In order to use the WIP flexibility measure and the time flexibility measure an optimization problem need to be solved in order to distribute the WIP quantities optimally on tools.

5.1. WIP balancing

For the WIP flexibility measure, a method has been developed and proved to be optimal in (Johnzén et al. 2008). Briefly, the method regards the WIP quantity for one recipe at a time. The WIP quantity of the recipe is distributed on the tool which currently has the least WIP. This is carried out until there is no more WIP quantity for the recipe or the WIP quantity of another tool becomes equal to the WIP quantity of the current tool. When two or more tools are considered to have the lowest WIP quantity, the WIP of the recipe is spread simultaneously on all these tools. This procedure is continued for all recipes until the WIP distributions of all recipes remain identical.

5.2. Time balancing

Since the time flexibility measure needs both well-balanced and properly minimized production times, the WIP balancing method cannot be used for the time flexibility measure. Approaches for similar problems have been studied in (Lawler and Labetoulle 1978), (Rossi 2003) and (Rossi et al 2005), but none of them are suitable for the time flexibility measure.

Instead an algorithm, based on the active set method (Rosen 1960), for optimally balancing the production times for the time flexibility measure, has been developed. The algorithm considers the WIP of one recipe at the time. But instead of starting to distribute WIP quantity on the tool with the lowest WIP quantity, the WIP of the recipe is distributed on the tools in such a way that the time flexibility measure will be maximized. This is done with the active set method. The method is developed in a similar way as in (Nash and Sofer 1996) using Wolfe condition (Wolfe 1969) in order to find a search direction for the optimal distribution. The procedure is repeated for all recipes until the WIP distributions of all recipes are optimal for the time flexibility measure.

The results in 4.2 illustrate that the original time flexibility measure might favor longer production times. Our research have indicated that this also will be troublesome for this time balancing method. Since the original time flexibility anyway does not model the capacity allocation well, it has been decided to only continue the research for the alternative time flexibility measure.

6. NUMERICAL EXPERIMENTS

A number of numerical experiments have been performed on data from a toolset with six tools where recipes with different WIP quantities are qualified.

6.1. Impact of qualifications

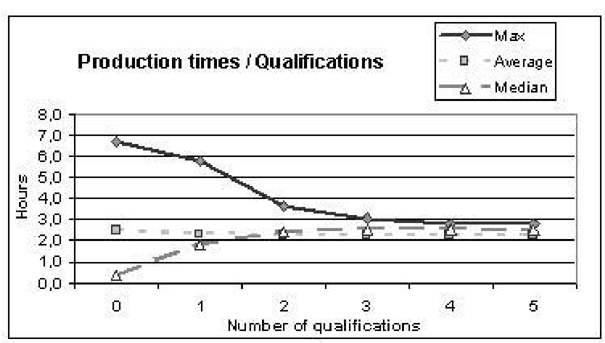

Figure 1: Production times after qualifications

Tests have been performed, to see how the production times on the tools can be affected by conducting those qualifications that will increase the time flexibility measure the most.

In Figure 1 and Figure 2, it can be seen how the production times for a toolset with six tools vary for each qualification. By performing only two qualifications, the maximum production time decreases by nearly 50 percent.

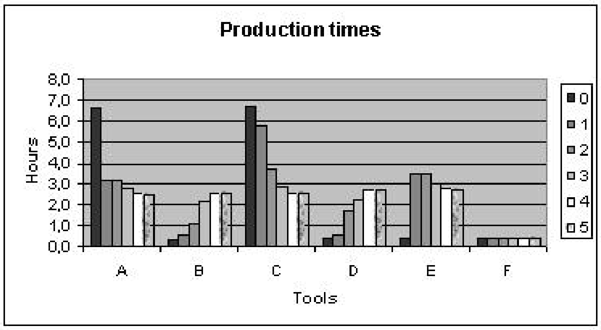

Figure 2: Production times per tool

The reason why the first qualification does not decrease the maximum production time as much as the second can be seen in Figure 2; at the beginning there are two tools with high production times, and two qualifications are needed to decrease the production times for both tools.

6.2. The flexibility balance exponent

As mentioned earlier, with different values of the flexibility balance exponent γ, it is possible to regulate the solutions of the WIP flexibility measure and the time flexibility measure. For the WIP flexibility measure, a more well-balanced WIP will still have higher value than a less well-balanced WIP. For the time flexibility measure, however, the flexibility balance exponent can be used to stress whether minimization of the total production time is more important in the measure than the balancing of the production times on the tools or the opposite.

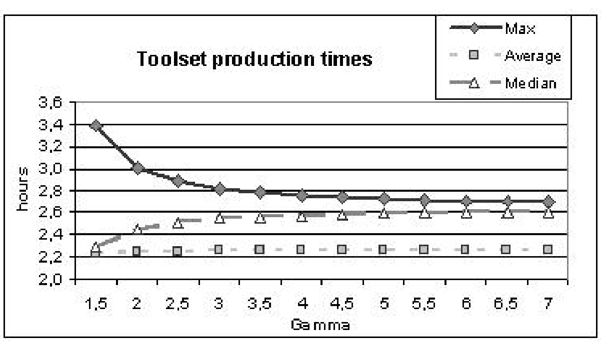

Figure 3: Production times for different values of γ

Using a small γ, the total production times – and hence also the average production times on the tools – are minimized but, at the same time, the maximum production time is allowed to stay quite high. Instead, by increasing γ, the production times on the tools become more and more balanced, and thus the maximum production time decreases at the same time as the average production time slightly increases.

In Figure 3, it can be seen that the lines converges as γ increases. For $\gamma > 3$, only small changes can be observed. As the computing times of the time flexibility balancing algorithm also increases when γ increases, it should be considered whether it is necessary to use higher values of γ.

6.3. Time flexibility versus WIP flexibility

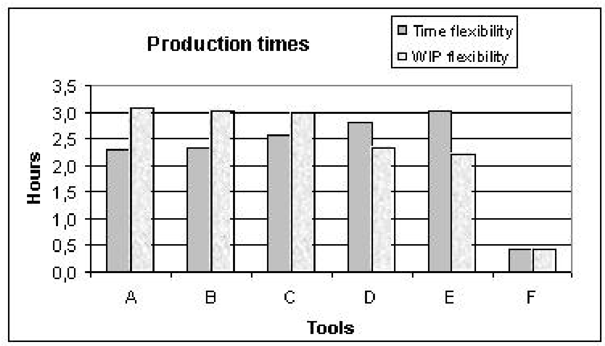

Figure 4: Production times on tools in a toolset

To see how the production times differ, an optimal solution for the alternative time flexibility measure ($\gamma = 4$) was compared with an optimal solution for the WIP flexibility measure. The production times for the two solutions on six tools in a toolset are shown in Figure 4. The total production times for the solutions are 13.44 hours (time flexibility) and 13.99 hours (WIP flexibility). The maximum production times are 3.01 (time flexibility) and 3.07 (time flexibility). For the same solutions, the WIP quantities are distributed as in Figure 5.

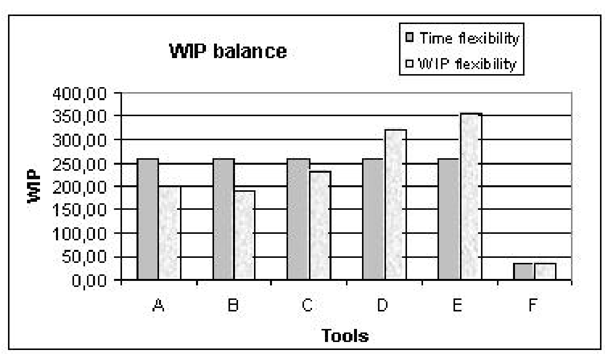

Figure 5: WIP quantities on tools in a toolset

The tool with the maximum WIP quantity is tool E with a WIP quantity of 356 for the time flexibility solution – this is a tool which generally has high throughput times. Since the WIP is well balanced, the WIP quantity is equally large on five of the six tools, 259. Due to the fact that there are not so many qualified recipes on tool F, there is only a WIP quantity of 34 on this tool.

7. CONCLUSIONS AND PERSPECTIVES

It has been shown that the developed measures accurately model the flexibility of a set of tools in a semiconductor fabrication facility. Numerical experiments have shown that even a small number of qualifications – conducted in accordance with the flexibility measures – can significantly improve the production times for a toolset.

The toolset flexibility measure models whether the WIP quantity for each recipe has sufficient capacity to be processed. An alternative formulation of the toolset flexibility has been developed, which considers how much some of the WIP quantity of a recipe can be spread on each tool. It has been shown that the alternative measure more accurately indicates where new qualifications should be conducted.

Furthermore, the WIP flexibility measure models the ability to balance the total WIP quantity on the tools. If the system cannot be well balanced, the operators of the fab do not have as good flexibility to process the WIP quantities where they are needed. A short description on how the WIP quantities can be optimally balanced has been shown.

The time flexibility measure models how well the process times can be balanced on the tools. To do that in a proper way, production times need to be both balanced and minimized. It has been shown how, using the flexibility balance exponent γ, it is possible to regulate whether the balancing aspect or the minimizing aspect should be considered the most. An alternative time flexibility measure has been proposed. We have shown that the alternative measure should be used, since it better considers minimization of the production times.

A way to optimally distribute the WIP quantities for the time flexibility measure has briefly been presented; an algorithm based on the active set method. It is still needed to prove that this method is optimal. Tests have shown promising results for the alternative time flexibility measure.

The system flexibility measure combines the effects of the other flexibilities. With the alternative measure, it is possible to regulate how each of the flexibilities should contribute to the overall system flexibility.

In practical setting, qualifications can be done at different levels, since some qualifications are harder to conduct than others. We are currently working on how these levels can be defined, and in which way this classification will affect the choice of the optimal qualifications.

We are also developing algorithms for finding the optimal qualifications when more than one qualification may be conducted at a time.

Tests have been initiated to show how qualifications based on the flexibility measures affect the results from a photolithography dispatcher simulator (Yugma et al 2007).

Finally, we are studying two other cases encountered in practice: (1) the dynamic case where WIP quantities are changing over time and (2) the case where recipes are not always available on a tool and when tools are not always available.

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