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IDEAL AND POTENTIAL FLEXIBILITY MEASURES FOR QUALIFICATION MANAGEMENT IN SEMICONDUCTOR MANUFACTURING

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ABSTRACT

In semiconductor manufacturing facilities, workstations are defined as sets of non-identical machines that are able to process different product types. Depending on production volumes, the product-to-machine configuration and how products are allocated to machines, a specific workload balance on the toolset can be obtained. WIP and Time flexibility measures were proposed to determine how well the workload is distributed over the toolset compared to an ideal situation where all the machines have the same workload level. However, for many workstations, this ideal situation is not reachable due to configuration limitations. Hence, in this paper, we define complementary indicators, called potential flexibility measures. Computational experiments on industrial data show how these new indicators refine our understanding of qualification configuration. A robustness factor is also presented that can be used in all flexibility measures to improve the quality assessment of the workload balance.

1 INTRODUCTION

Semiconductor manufacturing is a highly competitive industry which needs substantial investments on technology and huge facilities to satisfy the constant evolution of client requirements. A wide product mix in addition to a varying demand and the associated risks with the manufacturing system requires a strategy that enables these facilities to be flexible enough to reach the desired level of responsiveness. In wafer production facilities, called *fabs*, workshops or toolsets are composed of non-identical machines that are able to perform different process operations. Each operation has its own specific instructions when processed on a machine, which is called a *recipe*. To carry out a process on a given machine, the recipe has to be *qualified*, meaning it has been tested and authorized. If a machine is able to process a recipe but is not authorized to do so, the recipe is defined as *qualifiable*. Qualifying a recipe on a tool has a cost in terms of machine and operator time, auxiliary equipment, consumables used, etc.

Qualification management is a strategy to deal with this challenge and its goal is to determine which qualifications must be conducted on the toolset in order to improve its performance at the lowest cost. To determine the best qualifications, four flexibility measures were defined in Johnzén et al. (2011) to model the robustness and the workload balance of the toolset. In this paper, we only focus on the two measures related to workload balance: WIP and Time flexibility.

In the related literature, the WIP and Time flexibility measures are based on the comparison of the optimal workload balance on the set of qualified machines to an ideal balance where all machines are qualified. But this ideal situation is usually not feasible because, in wafer fabs, not all machines are able to process all recipes. To identify what is actually possible, we define *potential flexibility measures* to complete the existing measures, referred now as *ideal flexibility measures*. The idea is to evaluate the current qualification configuration of the system against a potential situation instead of an ideal one. After reviewing the literature in Section 2, the need for potential flexibility will be motivated in Section 3. Section 4 defines the new potential flexibility measures. The industrial application and some numerical experiments are given in Section 5. Section 6 introduces a robustness factor to add in our flexibility measures, before concluding in Section 7 where some perspectives regarding this work are developed.

2 LITERATURE REVIEW

Flexibility in the manufacturing field has been studied during the last decades to face the continuous changes of the market and the inherent system variability. Flexibility as a general concept is defined by Gupta and Goyal (1989) "as an adaptive response of the system to unpredictable situations" or defined in Gupta and Somers (1992) as "the ability to cope with changing circumstances or instability caused by the environment". From the manufacturing point of view, the flexibility concept is very complex to define since it depends on multiple factors. Nevertheless, according to Beach et al. (2000), the manufacturing flexibility is defined as "the ability of the system to quickly adjust to any change in relevant factors like product, process, loads and machine failure".

Qualification management in relation with manufacturing flexibility has been the object of several valuable studies in the semiconductor industry throughout the last decade. Aubry et al. (2008) proposed a Mixed Integer Linear Program (MILP) to find the qualification configuration that results in the optimal workload balance over the toolset at minimum cost while satisfying the demand. The link between flexibility and qualification management has been established by Johnzén et al. (2011), which proposed four flexibility measures to assess the qualification configuration of a workstation. According to the authors, by qualifying the right recipe-to-machine pair, the system flexibility can be increased by determining which configuration provides the highest flexibility. Johnzén et al. (2007) noted the importance of qualification management for wafer fabs, focusing on the fact that, by performing the right qualifications, the overall machine and operation efficiency of the workshop can be improved. In Johnzén (2009), models and solution approaches to obtain flexibility measures are introduced as well as the development of a software suggesting which qualifications to conduct. Rowshannahad and Dauzère-Pérès (2013) study qualification management with batch size constraints. Rowshannahad et al. (2014) study the relationship between qualification management and production variability and how workload variability can be reduced by conducting the right qualification. The impact of qualification management on scheduling has also been covered in Johnzén et al. (2008), where qualifications are used to see how increased flexibility leads to better scheduling.

3 PROBLEM DESCRIPTION

3.1 Ideal Flexibility Measures

Johnzén et al. (2011) defines four flexibility measures: Toolset flexibility determines how products can be performed on multiple machines while WIP and Time flexibility evaluate the workload distribution of the product volumes among the set of machines. System flexibility is a global indicator that takes all previous measures into account with a linear combination. We call these measures *ideal* because they are defined by comparing the optimized workload balance of the current system to an ideal workload balance where all recipes are qualified on all machines. To compute the WIP and Time flexibility measures, the following parameters are used:

R: Number of recipes,
M: Number of machines,
WIP_r: WIP quantity of recipe r (to allocate on the machines),
$Q_{r,m}$: Indicates the qualification status of recipe r on machine m, $Q_{r,m} = 0$ if recipe r cannot be qualified on machine m, $Q_{r,m} = 1$ if recipe r is qualifiable on machine m, and $Q_{r,m} = 2$ if recipe r is already qualified on machine m,
$TP_{r,m}$: Throughput rate of recipe r on machine m (number of wafers per hour),
γ: Workload balancing exponent ($\gamma \geq 1$),

and the following variables:

$WIP_{r,m}$: WIP quantity of recipe r allocated to machine m.

3.1.1 Ideal WIP Flexibility

The ideal WIP flexibility, noted F^{WIP}_{Ideal}, aims at assessing the quality of the optimal workload balance over the toolset. The next equation states F^{WIP}_{Ideal}:

$$F^{WIP}_{Ideal} = \frac{\left(\frac{\sum_{r=1}^{R} WIP_r}{M}\right)^{\gamma}}{\frac{\sum_{m=1}^{M}\left(\sum_{r=1}^{R} WIP_{r,m}\right)^{\gamma}}{M}} \in (0,1]. \tag{1}$$

Note that, because the numerator is a constant, maximizing F^{WIP}_{Ideal} is performed by minimizing the denominator with the constraints: $\sum_{m=1,Q_{r,m}=2}^{M} WIP_{r,m} = WIP_r, \forall r \in 1,\ldots,R$ (see for instance Rowshannahad et al. (2015)).

The workload exponent γ is used to adjust and amplify the importance of the workload balance when needed. A higher value of this parameter will favor a better workload balance whereas a smaller value will favor minimization of the total process time.

3.1.2 Ideal Time Flexibility

The ideal Time flexibility measure, noted F^{Time}_{Ideal}, evaluates the optimal workload balance in terms of process time. In contrast with F^{WIP}_{Ideal}, this measure takes into account throughput rates for each recipe-to-machine pair which could significantly change the WIP quantities allocated to the tools. The next equation recalls the ideal Time flexibility measure:

$$F^{Time}_{Ideal} = \frac{IdealTimeRatio}{\sum_{m=1}^{M}\left(\sum_{r=1}^{R}\frac{WIP_{r,m}}{TP_{r,m}}\right)^{\gamma}} \in (0,1], \tag{2}$$

where $IdealTimeRatio$ is the value obtained by minimizing the denominator expression $\sum_{m=1}^{M}\left(\sum_{r=1}^{R}\frac{WIP_{r,m}}{TP_{r,m}}\right)^{\gamma}$ when all the machines are virtually qualified to process all recipes, i.e. with the constraints: $\sum_{m=1}^{M} WIP_{r,m} = WIP_r$, $\forall r \in 1,\ldots,R$.

Then, as for F^{WIP}_{Ideal}, maximizing F^{Time}_{Ideal} is performed by minimizing the denominator with the constraints: $\sum_{m=1,Q_{r,m}=2}^{M} WIP_{r,m} = WIP_r$, $\forall r \in 1,\ldots,R$ (see for instance Rowshannahad et al. (2015)).

3.2 Limitation of Ideal Flexibility Measures

To illustrate this limitation, let us use an example of an industrial instance characterized by 12 477 wafers distributed among 58 recipes and that can be processed by a set of 18 heterogeneous machines with specific throughput rates per recipe. The recipe-to-machine configuration gives a total of *143 qualified pairs (recipe, machine)* and *36 qualifiable pairs (recipe, machine)*, in contrast with *1 044 possible pairs (recipe,machine)* if all recipes could be qualified on all machines. A workload balance exponent $\gamma = 6$ is used, which was shown to be suitable based on our industrial experiments.

To compute both flexibility measures, an optimal workload balance must be determined to compute the denominator. This paper does not aim at presenting the optimization methods, which can be found in Rowshannahad et al. (2015). In Figure 1.a, the resulting optimal workload balance is not equally distributed on the toolset whereas, in Figure 1.b, the perfect workload balance ensuring a maximal flexibility measure of 100% is shown. F_{Ideal}^{WIP} in (1) assesses this optimal workload balance against the ideal configuration which leads to a value of 31.4%, which is far from 100%.

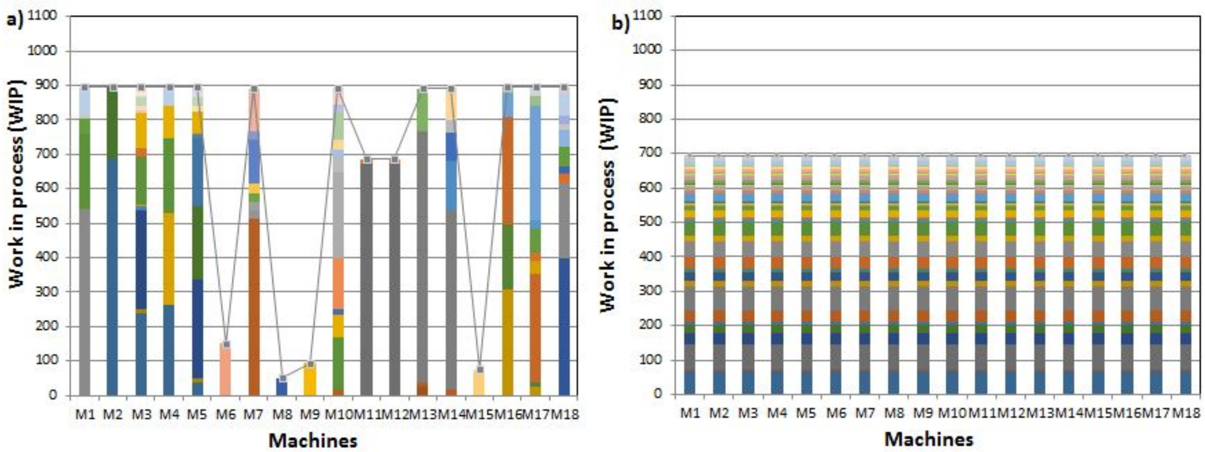

Figure 1: Toolset optimized WIP workload balances,
a) current configuration with $F_{Ideal}^{WIP} = 31.4\%$, b) ideal configuration with $F_{Ideal}^{WIP} = 100\%$.

Additionally, in Figure 1.a, note that machines 6, 8, 9 and 15 are not as loaded as other machines because they are qualified for only one recipe and the WIP quantities associated to these recipes are relatively small. It would be interesting to perform more qualifications on these machines to better balance the workload. With $F_{Ideal}^{WIP} = 31.4\%$, which is far from 100%, one can expect to find some qualification(s) that will lead to drastic improvements of the flexibility. However, with the current configuration, the maximum WIP flexibility measure that can be reached is 37.2% if all 36 qualifiable pairs (recipe, machine) are selected. In practice, not every qualification is possible because machines are actually not capable of performing some recipes or because qualification costs are too high. Hence, we would like to identify when the flexibility cannot be improved because of the current recipe-to-machine configuration. This is where the potential flexibility measures proposed in the next section are used.

4 POTENTIAL FLEXIBILITY MEASURES

We propose *potential* flexibility measures to answer the need of evaluating flexibility against a configuration that is attainable rather than an ideal one.

4.1 Potential WIP Flexibility Measure

F_{Poten}^{WIP} is designed to compare the optimal workload balance over the current configuration of qualified pairs (recipe, machine) against the optimal workload balance where all the qualifiable pairs (recipe, machine) are selected (potential configuration). This indicator provides a reachable balance reference instead of comparing with an ideal balance that cannot be achieved, and is defined as follows:

$$F_{Poten}^{WIP} = \frac{PotentialWIPRatio}{\sum_{m=1}^{M} (WIP_m)^{\gamma}} \in (0,1]. \quad (3)$$

As opposed to (1), the numerator *PotentialWIPRatio* of (3) is not a simple average of the total WIP over the toolset. It is the optimal workload balance when both the qualified pairs (recipe, machine) and the qualifiable pairs (recipe, machine) are selected. It is the minimum of the expression in the denominator $\sum_{m=1}^{M} (WIP_m)^{\gamma}$ with the constraints: $\sum_{m=1,Q_{r,m}\geq 1}^{M} WIP_{r,m} = WIP_r$, $\forall r \in 1,\ldots,R$. The same approach than for optimizing the denominator can be used.

Hence, computing F_{Poten}^{WIP} involves solving an optimization problem for both the numerator and the denominator.

4.2 Potential Time Flexibility Measure

F_{Poten}^{Time} evaluates the optimal workload balance of the current configuration in terms of process times compared to the optimal workload balance of the potential configuration in terms of process times, and is written below:

$$F_{Poten}^{Time} = \frac{PotentialTimeRatio}{\sum_{m=1}^{M} \left(\sum_{r=1}^{R} \frac{WIP_{r,m}}{TP_{r,m}}\right)^{\gamma}} \in (0,1], \quad (4)$$

where *PotentialTimeRatio* is the value obtained by minimizing the following expression in the denominator $\sum_{m=1}^{M} \left(\sum_{r=1}^{R} \frac{WIP_{r,m}}{TP_{r,m}}\right)^{\gamma}$ when all the qualifiable pairs (recipe, machine) are virtually selected, i.e. with the constraints: $\sum_{m=1,Q_{r,m}\geq 1}^{M} WIP_{r,m} = WIP_r$, $\forall r \in 1,\ldots,R$.

4.3 Illustration of Potential Flexibility Measures on an Industrial Instance

This section is using the same data as in Section 3.2 but with flexibility measures computed using (3). As expected, the optimal balance in Figure 2.a for the current configuration is similar to the one in Figure 1.a. On the opposite, the optimal balance for the numerator (potential configuration) shown in Figure 2.b has changed when comparing to Figure 1.b. It can be observed that, after virtually selecting the 36 qualifiable pairs (recipe, machine), a perfect distribution of the workload over the toolset cannot be reached. Furthermore, note that the potential balance does not differ very much from the current balance, which is evidenced by the fact that $F_{Poten}^{WIP} = 84.5\%$.

Note that, for this specific configuration, an ideal balance cannot be obtained because there are no qualifications with enough WIP quantities that could let machines M6, M8, M9 and M15 achieve the same workload level as the other machines. In general, it makes more sense to qualify recipes that enable less loaded machines to be rebalanced, in particular recipes that combine relatively high WIP quantities on poorly loaded machines. Qualifications of recipes on machines that are already sufficiently loaded often do not improve the workload balance.

The main interest of potential flexibility measures is that they help to identify when there is no margin to improve the system based on its current boundaries, i.e. the set of qualifiable pairs (recipe, machine). In Table 1, note that, for the same instance and after performing three qualifications, $F_{Poten}^{WIP} = 100\%$. Hence, nothing can be gained through additional qualifications among the set of qualifiable pairs (recipe, machine). In contrast, after three qualifications, F_{Ideal}^{WIP} increases to 37.2%, so significant gains are expected by selecting new (currently non-qualifiable) qualifications. However, identifying these qualifications is difficult and requires the help of experts.

Figure 3 illustrates that the potential flexibility measures detect that the maximal potential performance of 100% has been reached after three qualifications, whereas the WIP ideal flexibility measure is never larger than 37.2%.

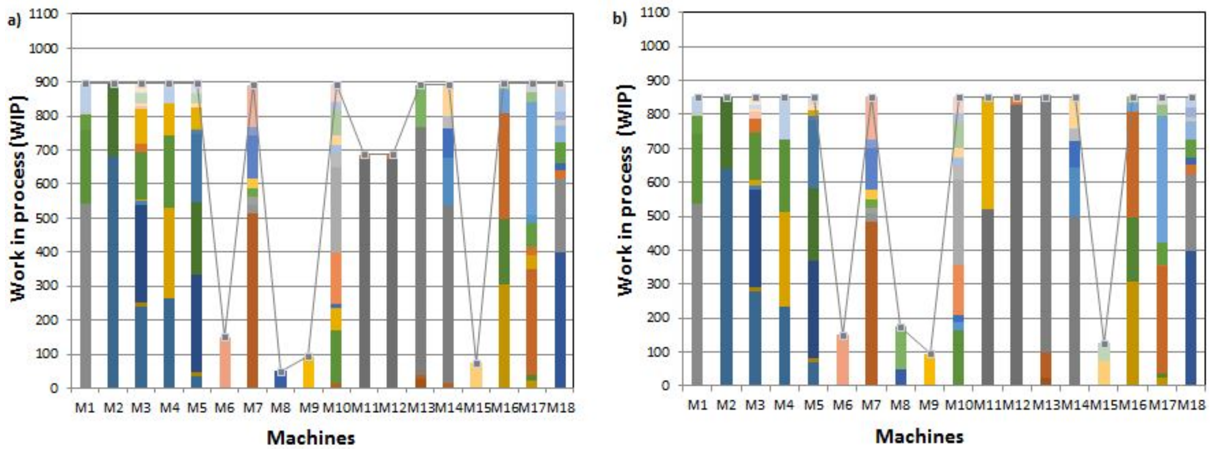

Figure 2: Toolset optimized WIP workload balances,
a) current configuration with $F^{WIP}_{Poten} = 84.5\%$, b) potential configuration with $F^{WIP}_{Poten} = 100\%$.

Table 1: WIP flexibility gains by conducting 1, 2, or 3 qualifications.

Number of Qualifications	Ideal		Potential	
	Gain(%)	*Flex (%)*	*Gain(%)*	*Flex (%)*
0	-	31.4	-	84.5
1	2.7	34.1	7.2	91.6
2	2.2	36.3	5.9	97.5
3	0.9	37.2	2.5	100.0

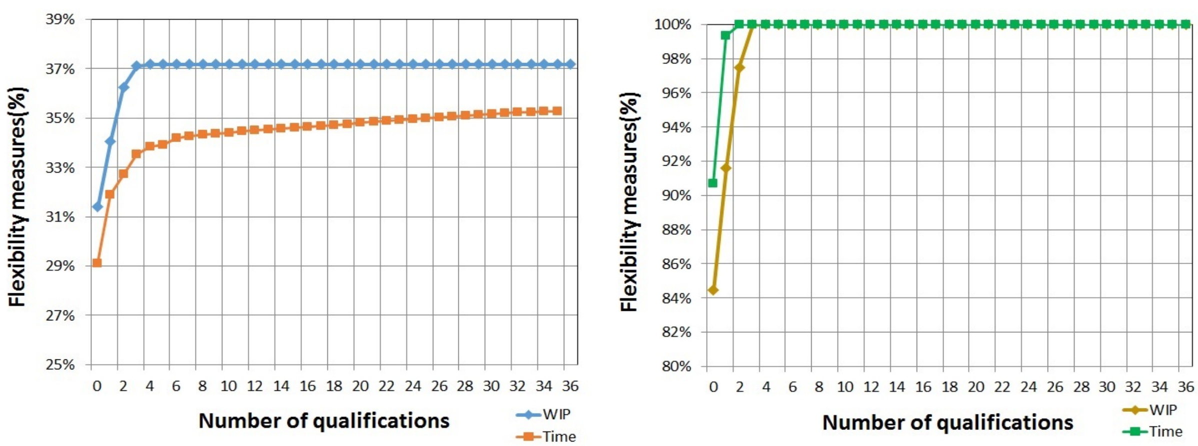

Figure 3: WIP and time flexibility measures versus number of qualifications,
a) ideal flexibility, b) potential flexibility.

Ideal and potential flexibility measures are both important and are complementary to analyze the situation. The ideal measures assess how well the toolset is currently balanced compared to a perfectly balanced workload balance, which is the ultimate goal, whereas the potential measures show how close is the current configuration to a configuration where all allowed qualifications are performed.

5 IMPLEMENTATION AND RESULTS ON INDUSTRIAL INSTANCES

5.1 Implementation

An application was developed on Microsoft Excel and the algorithms to compute flexibility measures and optimal workload balances were coded in VBA. The application has two modes. The first mode is dedicated to the calculation of flexibility measures for the current qualification configuration and to display its optimal workload balance. Flexibility measures of the current configuration are used as reference values to assess the effect of conducting additional qualifications while the workload balance includes the detailed recipe-to-machine allocation. The second mode is used to determine the combinations of qualifications that result in the largest flexibility improvements. In this mode, the application provides a list of sets of new qualifications ranked and ordered by decreasing flexibility gains, as well as the associated flexibility measures after virtually selecting each of these sets of qualifications.

5.2 Results

The application has been tested with industrial data from the photolithography workshop. We used 25 instances that are characterized by a set of 18 non-identical machines, a variable amount of recipes ranging from 27 to 71, and variable WIP quantities ranging from 2 000 to 25 000 wafers. It it important to point out that, in order to emphasize workload balance in the optimization, experiments were conducted with a workload balance exponent of $\gamma = 6$.

Simulation results are shown in Table 2 where, for each instance, the flexibility measures (WIP and Time, ideal and potential) for the current configuration as well as the flexibility gain after conducting the best single qualification are provided.

Globally, the average F_{Ideal}^{Time} for the 25 instances is 10.1% while the average F_{Poten}^{Time} is 54.1%. These results show that, in general, the workload balances of these instances are quite far from the ideal distribution. Nevertheless, through potential flexibility measures, it is possible to see that there is still on average a possible improvement of 45.9% ($100\% - 54.1\%$). Concerning the flexibility gain, after performing the best qualification, the average gain on F_{Ideal}^{Time} is 3.6% while it is 25.7% on F_{Poten}^{Time}. These results show that, after selecting the first best qualification, there is not too much improvement of the ideal flexibility measure. On the opposite, the potential flexibility increases substantially by 25.7%, leading to a flexibility measure of 79.8% ($54.1\% + 25.7\%$), which is a major improvement on the best potential workload distribution.

When considering the choice of the best qualification(s), both ideal and potential flexibility measures suggest the same results for the ranked list of qualifications. However, potential flexibility offers the advantage of measuring the relative importance of each qualification considering the real margins of improvement of the system. It is possible to see when the workload balance can no longer be improved. For example, looking at instance 16, one could think that additional qualifications should be performed because $F_{Ideal}^{WIP} = 0.2\%$. However, since $F_{Poten}^{WIP} = 99.1\%$, it is possible to see that there is not much to gain with the allowed qualifiable pairs (recipe, machine). In this case, the user should question the current degrees of freedom within the qualification matrix to check whether new qualifiable pairs (recipe, machine) can be added.

Another interesting case is instance 24, where F_{Ideal}^{WIP} is also very small (0.1%) but F_{Poten}^{WIP} is equal to 24.4%. As the gain to carry out one qualification is not significant for F_{Ideal}^{WIP} (0.2%), the user would think there is no use to carry out new qualifications. However, the gain of 46.1% on the potential flexibility measure is actually quite large, which shows that carrying out qualification would bring significant improvement to the system flexibility.

Table 2: Results of ideal and potential flexibility measures and flexibility gains after the best qualification for 25 industrial instances.

Instance	**Initial configuration** (%)				**Gain after best qualification** (%)			
(Nb of recipes)	F^{WIP}_{Ideal}	F^{Time}_{Ideal}	F^{WIP}_{Poten}	F^{Time}_{Poten}	ΔF^{WIP}_{Ideal}	ΔF^{Time}_{Ideal}	ΔF^{WIP}_{Poten}	ΔF^{Time}_{Poten}
Data 1 (71)	8.2	27.7	91.6	92.3	0.5	1.4	5.3	4.6
Data 2 (38)	1.1	5.7	44.4	51.1	1.1	4.3	44.9	38.2
Data 3 (35)	1.6	5.6	17.3	19.6	1.5	5.2	16.3	18.0
Data 4 (31)	1.4	18.2	35.9	56.6	2.4	10.3	60.5	32.0
Data 5 (27)	4.6	39.1	38.6	67.6	6.9	15.0	57.7	26.0
Data 6 (36)	0.0	0.2	13.7	14.3	0.1	1.2	82.5	81.7
Data 7 (41)	1.9	8.7	57.2	65.7	1.2	2.6	37.5	19.6
Data 8 (54)	1.2	5.8	28.6	57.8	1.9	3.0	45.7	30.1
Data 9 (56)	2.3	6.9	36.3	45.6	0.7	3.2	10.5	21.1
Data 10 (58)	5.4	3.3	42.3	29.5	3.0	2.7	23.9	24.3
Data 11 (66)	8.0	6.9	63.9	54.7	1.9	1.5	14.9	12.1
Data 12 (64)	2.2	1.7	29.4	25.6	1.4	1.5	18.7	22.9
Data 13 (58)	31.4	29.1	84.5	90.7	2.7	2.8	7.2	8.7
Data 14 (45)	0.2	0.3	69.7	51.9	0.0	0.1	11.9	19.5
Data 15 (31)	9.6	24.4	67.8	59.0	3.7	14.7	26.0	35.5
Data 16 (48)	0.2	0.9	99.1	98.8	0.0	0.0	0.7	0.6
Data 17 (28)	0.4	8.6	79.3	77.5	0.1	2.5	20.7	22.3
Data 18 (41)	0.6	1.5	57.7	23.1	0.4	4.8	42.1	76.1
Data 19 (45)	0.4	0.7	13.1	7.0	1.9	7.3	68.1	73.1
Data 20 (50)	0.4	0.8	92.0	96.1	0.0	0.0	8.0	3.6
Data 21 (59)	11.4	19.0	84.6	86.8	1.0	1.3	7.2	5.8
Data 22 (53)	0.2	0.2	18.0	5.9	0.3	0.3	12.8	8.9
Data 23 (48)	8.6	33.0	93.1	77.2	0.2	3. 0	2.4	7.0
Data 24 (44)	0.1	0.9	24.4	20.9	0.2	1.7	46.1	39.7
Data 25 (43)	0.3	2.7	95.7	77.3	0.0	0.4	2.4	11.3
Average	4.1	10.1	55.1	54.1	1.3	3.6	27.0	25.7

6 INTRODUCTION OF ROBUSTNESS FACTOR

6.1 Limitation of Ideal and Potential Flexibility Measures

Both ideal and potential flexibility measures help in the qualification management process. However, another limitation is encountered by both types of measures when the initial flexibility value is equal to 100% and there is no new relevant qualification since the WIP allocation is already perfectly balanced. This is the case in Figure 4 where F^{Time}_{Poten} is equal to 100%. However, if we compare the total process time of all qualified wafers on each machine to its workload allocation, then it is interesting to note that these two times are relatively close for some machines such as $M9$ or $M10$, whereas the first time is much larger than the second one for machines $M3$ and $M4$. In other words, machines $M9$ and $M10$ have to process almost every wafer that is qualified on them in order to meet the optimized workload balance. But this is very difficult to ensure at the operational level because of production variability. Not all qualified wafers will continuously arrive on the machine over time and thus the machine will be idle. A workload balance would be more robust if, for each machine, the total process time of all qualified wafers is much larger than its allocated workload as it is the case for machines $M3$ and $M4$.

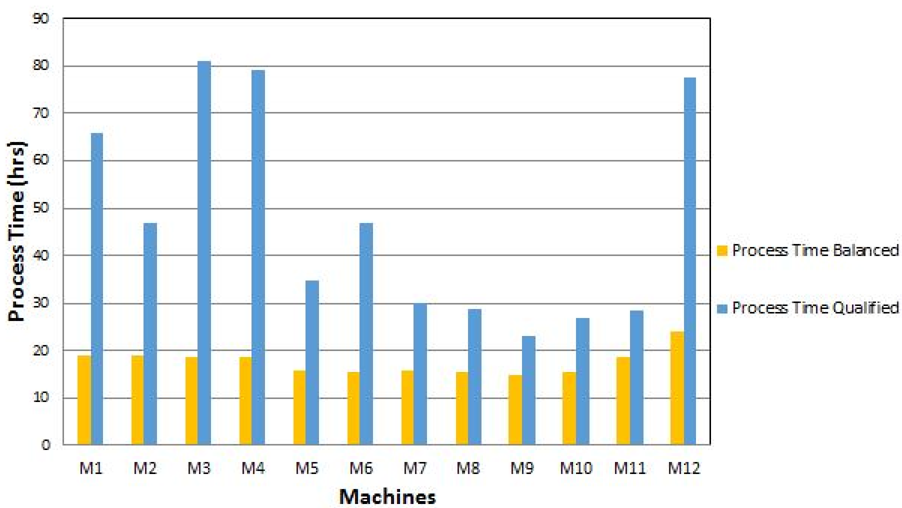

Figure 4: Allocated workload in optimized balanced workload vs total process time of all qualified wafers for each tool with $F^{Time}_{Poten} = 100\%$.

6.2 Robustness Factor

To assess the robustness of a workload balance, we propose to consider a robustness factor R in the flexibility measures, whether ideal or potential. This factor can be described as the minimum ratio we would like to ensure between the potential loading factor of a machine (sum of the processing times if all WIP quantities of all recipes that are qualified on the machine are assigned to the machine) divided by its allocated workload in the workload balance. For instance, the ideal time flexibility measure is defined as follow:

$$F^{Time}_{Ideal,r} = \frac{IdealTimeRatio}{\sum_{m=1}^{M}\sum_{r=1}^{R}\left(\frac{WIP_{r,m}}{TP_{r,m}}\right)^{\gamma}(1+RI_m)} \in (0,1], \tag{5}$$

where $RI_m = \max(0, \frac{R\left(\sum_{r=1}^{R}\frac{WIP_{r,m}}{TP_{r,m}}\right)-\left(\sum_{r=1;Q_{r,m}=2}^{R}\frac{WIP_r}{TP_{r,m}}\right)}{R\left(\sum_{r=1}^{R}\frac{WIP_{r,m}}{TP_{r,m}}\right)}) \in [0,1]$.

The optimization of *IdealTimeRatio* also takes into account the robustness factor. There is no impact on the flexibility measures if $R = 1$. As it is not obvious that optimizing (2) is equivalent to optimizing (5), we decided to use $F^{Time}_{Ideal,r}$ as an indicator of the quality of a robust workload balance whereas F^{Time}_{Ideal} remains the optimized flexibility measure. Additional experiments need to be conducted to analyze how the robustness factor impacts flexibility measures and what value of R is adapted in our industrial instances.

7 CONCLUSION AND PERSPECTIVES

In this work, we pursued the development of models and solution approaches for flexibility measures in the context of qualification management in the semiconductor industry. We have proposed some adapted models of flexibility measures that we named potential flexibility measures. Through these models, the optimal workload balance for the current qualification configuration is now compared to the optimal workload balance of the configuration in which all the potential qualifications have been performed. The comparison of the current versus the potential configuration provides a measurement of the real possibilities of improvement of the system. It is important to note that the ideal and potential flexibility measures are both important to analyze the system because they complement each other. Additionally, to assess the robustness of all balances evaluated (ideal and potential), a robustness factor has been defined. Further experiments need to be conducted to determine how it impacts flexibility measures as well as an adapted factor value for industrial instances.

A software was developed and implemented to assess industrial qualification configurations with flexibility measures. This new tool is part of a qualification decision support system and its main goal is to suggest the best qualifications to perform that deliver the higher flexibility gain for the system. The application calculates WIP and Time flexibility measures under ideal and potential modes. The application was validated on 25 industrial instances.

Additional aspects can be taken into account in qualification management. From the industrial point of view, a need has emerged to test scenarios involving multiple qualifications instead of simple qualifications, as for instance qualifying one recipe on a machine may qualify at the same time similar recipes. Each scenario is composed of groups of recipes to be qualified and/or disqualified on different machines at the same time. Instead of searching the best qualification, the decision support system would rank the different tested scenarios. This functionality will help to cover the case of non-compatible recipes, such as the use of non-compatible resins in the photolithography area.

Another important element that can be incorporated is the capacity of machines in terms of their availability to perform recipes as in Rowshannahad et al. (2015). Finally, batching constraints in some workshops such as the diffusion area are also relevant to consider as in Rowshannahad and Dauzère-Pérès (2013).

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