Proceedings of the 2015 Winter Simulation Conference
L. Yilmaz, W. K. V. Chan, I. Moon, T. M. K. Roeder, C. Macal, and M. D. Rossetti, eds.

SIMULATION MODEL TO CONTROL RISK LEVELS ON PROCESS EQUIPMENT THROUGH METROLOGY IN SEMICONDUCTOR MANUFACTURING

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ABSTRACT

This paper first presents a simulation model implemented to study a specific workcenter in semiconductor manufacturing facilities (fabs) with the objective of controlling the risk on process equipment. The different components of the model, its inputs and its outputs, that led us to propose improvements in the workcenter, are explained. The risk evaluated in this study is the exposure level in the number of wafers on a process tool since the latest control performed for this tool, based on an indicator called Wafer at Risk (W@R). Our analysis shows that measures should be better managed to avoid lack of control and that an appropriate qualification strategy is required.

1 INTRODUCTION

The strategies of semiconductor manufacturing companies to improve their performance are based on performance measures such as yield, throughput and cycle time. To reach these objectives, control plans are used to supervise the behavior of process tools. Due to the complexity of this industry, a permanent review to check the effectiveness of control steps is necessary according to Bassetto and Siadat (2009).

To manufacture an integrated circuit, wafers pass through numerous process steps such as Photolitography, Etching, Chemical deposition and so on. This paper is focused on a particular step of semiconductor manufacturing: The Ion Implant workcenter. The aim is to analyze the behavior of its process tools and the risk levels through a simulation model, and to propose and validate approaches to reduce the risk.

Control methods are used to reduce risk. Different approaches can be found in the literature to manage risk. Risk analysis preventive tools such as Failure Mode and Effects analysis (FMEA) are used by Mollah (2005) to identify potential failures of a process before using it and to evaluate its subsequent effects. A prioritization of risk management measures can be found in Stewart (2001) using a risk-based approach. Khan and Haddara (2003) introduce a method following the same approach but also taking into account a preventive maintenance plan for process equipment. The importance of optimizing control plans in semiconductor manufacturing is studied by Nduhura Munga et al. (2015). They show that risk can be reduced without adding control measurement capacity.

In this study, the risk is evaluated as the number of wafers processed on a process tool since the latest control performed for this tool. The indicator is called W@R (Wafers at Risk) and corresponds to the possible loss in number of wafers in case of malfunction of the tool during the process. Let $NW(l)$ denote the number of wafers in lot l, $W@R_t$ denote the current wafers at risk of process tool t ($W@R_t$ evolves dynamically) and $W@R_t(l)$ denote the wafers at risk when lot l is completed on t. Then, $W@R_t$ and $W@R_t(l)$ are updated as follows when lot l is completed on t: $W@R_t := W@R_t + NW(l)$ and $W@R_t(l) = W@R_t$. If lot l that was processed on process tool t is measured, then $W@R_t$ is updated (i.e. decreased) as follows: $W@R_t := W@R_t - W@R_t(l)$ (see Figure 1 as an example). In the workcenter considered in this paper, a lot is measured just after having been processed (contrary to the defectivity control considered for instance in Rodriguez-Verjan et al. (2013)), hence $W@R_t := 0$ when a lot processed on t is measured (see Figure 2 as an example).

The structure of this paper is as follows. Section 2 defines the characteristics of the problem and Section 3 presents the simulation model. In Section 4, numerical results using industrial data help to analyze the current risk on process tools, and to compare with the case where additional products are qualified. Finally, conclusions and future perspectives are presented in Section 5.

2 PROBLEM DESCRIPTION

Ion Implantation in semiconductor manufacturing is a doping technique. Specific regions can be implanted with a precise control of doping levels modifying the conductivity of the semiconductor. The ion impacts alter the elemental composition of the wafer, otherwise each individual ion can cause point defects over the wafer surface. When a lot is measured to check that the process tool is not defective, the crystallographic damage is verified.

A route is the sequence of process operations required to obtain the final product. Along its route, each lot that usually contains 25 wafers enters several times into the Ion Implant workcenter to receive different processes depending on the dose levels (Arsenic, Boron, Phosphorus, etc.), energy (from 2 to 3000 KeV) and implant angles. The workcenter is divided in various process tool groups with different properties adapted to each possible treatment. There is a metrology area nearby where some lots are measured after being processed. Usually, a lot is only processed on one tool in the workcenter before being measured or directly continuing to other workcenters. In some cases, a lot may have to go through two or three consecutive Ion Implant operations. In these cases, the lot can always be measured after the first operation and sometimes after the following operations depending on the characteristics of the route of the lot.

Over the years numerous sampling techniques in semiconductor manufacturing have been developed as it is shown by Nduhura Munga et al. (2013). An important characteristic to take into account for the workcenter we are considering is that there is no Sampling Rate (defined as “1/N”, i.e. one lot is measured after “N” lots are processed) to perform a measure. It will also be interesting to tackle this issue in the future because it has been shown that, if the selection of lots to measure is done dynamically according to risk levels, useless measures can be avoided as proposed by Dauzère-Pérès et al. (2010). In our study, the lots belonging to a measurable product are flagged before entering the workcenter for the first time, and they are measured every time they visit the workcenter just after they have been processed.

This study is focused on building an Ion Implant simulation model with all the process and metrology tools based on the real behavior and data in a fab. The goal is to supervise the risk of every single process tool in terms of W@R values. Figure 1 illustrates the main information obtained by representing a W@R chart.

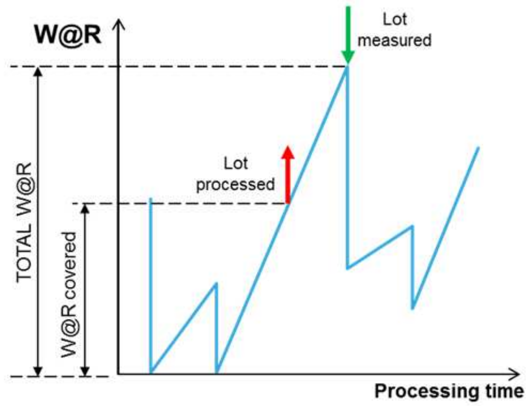

Figure 1: Wafer at risk (W@R) behavior for a process tool in the general case.

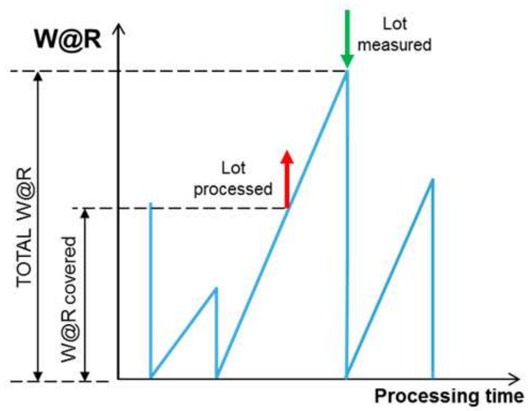

Figure 2: Wafer at risk (W@R) behavior for a process tool of Ion Implant workcenter.

The W@R corresponds to the number of wafers that could be potentially impacted if a problem occurs. As formalized in Section 1, the W@R of a process tool increases each time a lot is processed on the tool, and it decreases when a measure of a lot processed on the tool is completed. Measuring a lot, which confirms that it was processed correctly on a tool, validates the quantity of wafers in the previous lots processed on the tool. In this case, the W@R is reduced which means that the risk is decreased. The idea is to get dynamic W@R values for lots processed and measured to better analyze how the workcenter is operating. With a clearer view on how the real Ion Implant workcenter is running, the following steps are: Propose new approaches to reduce the risk, introduce them into the simulation model and apply the effective approaches in the real workcenter to change the current policies. Our goal is to later extend this work to other workcenters.

3 DESCRIPTION OF THE MODEL

The simulation model is divided into four parts: (1) Loading real data, (2) Model description explaining the flow of lots in the process and metrology tools, (3) Product qualification modeling, which is used to increase the number of lots to measure and (4) Model outputs, showing W@R values and metrology tool indicators.

3.1 Loading real data

It is essential for us to accurately simulate what happens in reality to validate potential improvements. To achieve this, industrial data are used as inputs to inject lots in the model. The data are taken from reports that contain what actually happened in the fab. A state chart manages this flow of lots. Lots processed and measured are registered in a table ordered by date. There, each row contains: The date when a lot was processed or measured, the tool which performed the operation, the lot ID, the operation, the number of wafers in the lot, the type of operation (process or measurement), the route name and the product name. When a simulation starts, the data are read and the lots enter in the model following the ordered sequence.

3.2 Model description

The workcenter has 17 process tools divided in 4 groups with different properties (Group A, Group B, Group C, Group D). Each group has its own behavior. Hence, if the W@R values of tools of the same group are compared, they should have be of the same order of magnitude, but tools of different groups could show differences. There are two metrology tools, Metro01 and Metro02, both with the same specifications except that one is faster.

The simulation model reproduces the arrival of the lots in the workcenter, their paths across various process or metrology tools and the exit towards the next process steps. The lot information gathered in Section 3.1 is associated to the current lot injected with all its parameters by the source called "incomingLots". As soon as a lot enters in the system, it is dispatched to the process area or the metrology area. In the case of the process area, there are four options according to the process tool. Figure 3 shows the structure of the simulation model.

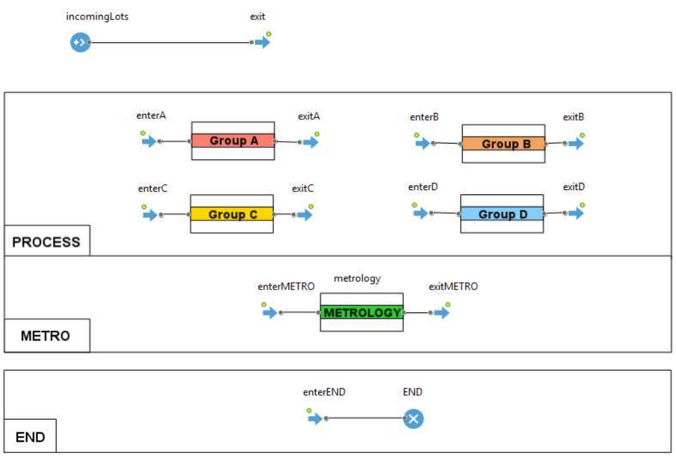

Figure 3: Ion Implant workcenter structure.

Once in a process tool group, a lot enters the tool fixed by its input parameter, and then two of its parameters are updated: Process tool and operation type. The purpose of refreshing these parameters is to confirm that the lot has been processed by the right tool. This is useful to evaluate future scheduling approaches, which could select another process tool instead of the one selected in the real data. After leaving the process tool, for instance tool A01, two counters for this particular tool increase: W@R and W@R_Max. The first one increases the same number of wafers in the lot, and the second counter only increases if the new W@R value is larger than the current W@R_Max. The metrology area operates equivalently. The lot is assigned to the fixed metrology tool and two parameters are overwritten with the selected metrology tool and to confirm that the operation type consists of a measure. Again, the idea of updating these two parameters is to propose and evaluate future approaches based on switching metrology tools. The configurations of process tool groups and metrology tools are shown in Figure 4.

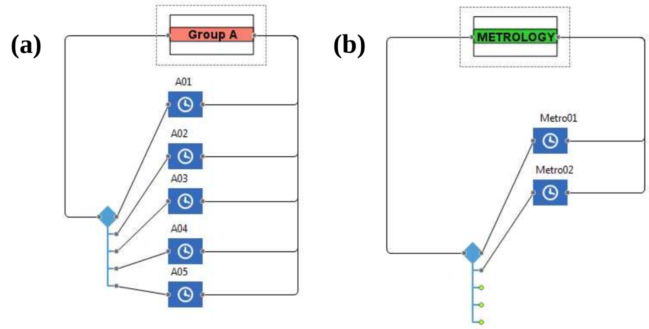

Figure 4: Process tool groups (a) and metrology tools (b).

When a lot exits from a process tool group or from the metrology area, a counter of processed lots and measured lots increase. The W@R value of a process tool decreases right after the measure of a lot that has been processed on this process tool. Hence, when a lot leaves the metrology area, the W@R value from the tool that has performed the process operation is set to zero, otherwise the value of W@R_Max remains unchanged. During the simulation, there is a table that dynamically shows both values for every process tool.

3.3 Product qualification modeling

Qualifying a product to be measured is highly time consuming for the engineers, since they must elaborate the recipe for the metrology equipment. Hence, a limited percentage of lots is available for measurement among all processed lots. Qualifying more products has been tested using the simulation model to evaluate the benefits of this strategy. Let us assume that it is possible to qualify any product. The lot, just after being injected in the workcenter and before going to process or metrology, is added to a queue of a fictitious "qualification area". The qualification area must check if the incoming lot belongs to a qualified product and, in this case, the lot is flagged to be measured. The model of this area is shown in Figure 5.

There are three main characteristics in the simulation model associated with qualifying a lot: The product, the route and the process operation. As inputs, two tables are introduced. The first table is a list with the new products to qualify, and the second table includes all current routes in the fab with their respective Ion Implant process operations. The routes also indicate, for every operation, whether it is possible to perform a measure or not (measuring after some process operations is not allowed, in particular for data collection reasons that could create noise in the Statistical Process Control charts monitoring the workcenter).

Every time a lot enters the product qualification area (see Figure 5), the first check (A) consists in verifying whether the lot belongs to a product that is qualified to be measured, otherwise, the lot is skipped (B) and is only processed. Then, the second check (C) consists in verifying whether the lot is at an operation in the route that allows a measure to be performed. If this is not the case, the lot is skipped (D) and is only processed.

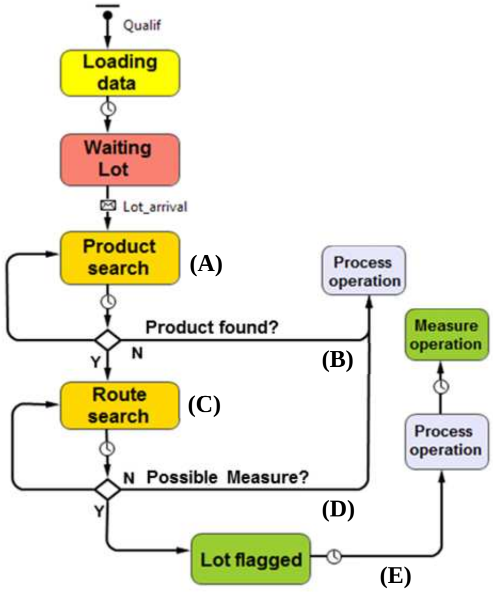

Figure 5: Product qualification diagram.

As a final stage, if the operation can be measured (E), the lot is flagged and, after being processed, is sent to metrology. There, metrology tools now have a queue, and are configured to perform the measure in 7 and 5 minutes for Metro01 and Metro02, respectively. The queue management aims at measuring lots as quickly as possible. So, if both metrology tools are available, the first option is Metro02 because it is the fastest tool. But, when both tools are busy and there are lots waiting to be measured, the queue management software calculates to which metrology tool the lot will be first assigned.

3.4 Model outputs

Our objective is manage the risk in terms of W@R for every process tool. Having relevant data and output charts to perform the analysis are key points of the simulation model. Thanks to the charts, we can detect whether a process tool is over or under controlled. Each process tool t has two parameters that are updated dynamically: $W@R_t$ (as already discussed in Section 1) and $W@R\_Max_t$. The updating of $W@R_t$ is discussed in Section 1 and, once $W@R_t$ is updated, $W@R\_Max_t$ is updated as follows: $W@R\_Max_t$:= Max($W@R\_Max_t$, $W@R_t$), i.e. $W@R\_Max_t$ only increases over time.

Each time a lot finishes at a process tool group or at the metrology area, a new row is registered in a table that is generated as an output at the end of simulation. This new row comprises: The time when the lot was processed or measured (in seconds), the lot ID, the product name, the number of wafers, the operation type (process or measure) and the process tool or metrology tool. The W@R parameters are also updated.

To sum up, while the simulation model is running, we can see how the W@R values of process tools vary. When the simulation ends, two W@R tables are created: one with the W@R values of lots when they are completed on their process tools, i.e. $W@R_t(l)$ for each lot l processed on tool t (see Section 1), and another table with the value of $W@R\_Max_t$ for each process tool t. Also, the set $ML(t)$ of measured lots for process tool t is stored.

4 NUMERICAL RESULTS

The numerical results in this section are obtained through the proposed simulation model that was implemented using the Anylogic software and with two weeks of real data from STMicroelectronics in Rousset, France. The data include around 21,000 process operations and 1,900 measures of lots. Two indicators for each process tool t are used: $W@R\_Max_t$ (as discussed in Section 3.4) and $W@R\_Average_t$, which is the average of W@R values attained just before a lot processed on t was measured, i.e. the average of W@R values of lots in the set $ML(t)$: $W@R\_Average_t = \sum_{l \in ML(t)} \frac{W@R_t(l)}{|ML(t)|}$.

First, the current risk on process tools is presented in Section 4.1. Then, Sections 4.2 and 4.3 show the possible improvements when a qualification strategy is followed.

4.1 System description

One of the constraints of the Ion Implant workcenter is that not all lots can be measured to reduce the risk. As already mentioned in Section 3.3, this is due to the difficulty for engineers to qualify a new product on metrology tools. This is why there are often no lots qualified to be measured that are available, and process tools reach large W@R values until a measure is performed to reduce the risk.

Table 1 shows the percentage of lots processed during two weeks in Ion Implant. It is divided into 6 products that are qualified to perform a measure and the other products. The impact of lots that are not covered for the metrology tools is 75.5%, and only 24.5% of lots are candidates to be measured. This leads to long periods without controlling process tools.

Table 1: Percentage of processed lots per product (only products 1 to 6 can be measured).

Products	**Processed lots (%)**
Product 1	7.8%
Product 2	3.1%
Product 3	0.8%
Product 4	5.9%
Product 5	5.8%
Product 6	1.1%
Other products	*75.5%*
Total	**100%**

4.2 Current situation

The W@R charts obtained after running the simulation model help to quickly find for which process tools we need to take action in order to improve their risk level, see for example Figure 6 where the behavior of two tools belonging to group A is shown. In the graphs, every time a lot is processed, the W@R of the corresponding process tool is increasing, and the peaks show the maximum W@R values that are attained before a measurement is performed. For confidentiality reasons, the axes have been normalized.

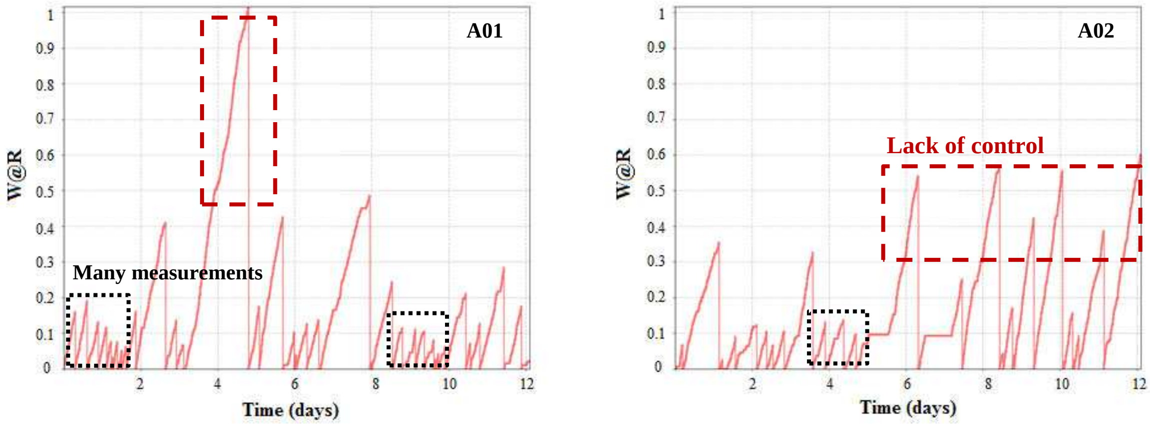

Figure 6: W@R evolution for process tools A01 and A02 for real data.

Normally, there are some areas with lack of control. The goal is to reduce the maximum W@R values to remain below the W@R limits and even to establish lower W@R limits. Looking at Figure 5 and a limit of 0.5, the W@R value exceeds the limit and a control operation has to be performed as soon as possible. When analyzing the measurement effectiveness for process tool A01, too many measures are sometimes performed, for instance before the beginning of the second day and between days 8 and 10. It is a waste of measurement capacity since control operations do not bring enough added value.

At this stage, we want to provide a general view of the risk in the workcenter and show that it is possible to avoid reaching large W@R values. As future perspectives, we want to develop a dynamic system to only select the right lots to measure and to avoid useless measurements.

4.3 Qualifying a single product

First, finding the best products to qualify is needed. With a treatment of the data obtained by running the simulation model on real data, a list is elaborated that takes all lots processed of products not covered into account and the routes with Ion Implant operations that can be measured. In this first study, the products that bring the largest number of additional measures are considered. Taking more aspects into account is considered as a future perspective.

The first six products are selected and each qualification has been simulated separately. Figure 7 shows the W@R evolution for process tools A01 and C04 when products 7 or 12 are qualified respectively. These two process tools have experimented the most remarkable W@R reductions compared to the other tools. Also, qualifying one of these two products provide the largest W@R reductions. The figure shows that, after qualification, most of the high peaks are reduced. For example, for process tool A01, the W@R between day 2 and day 5 is better distributed than before and, for process tool C04, it has considerably decreased between day 10 and day 12.

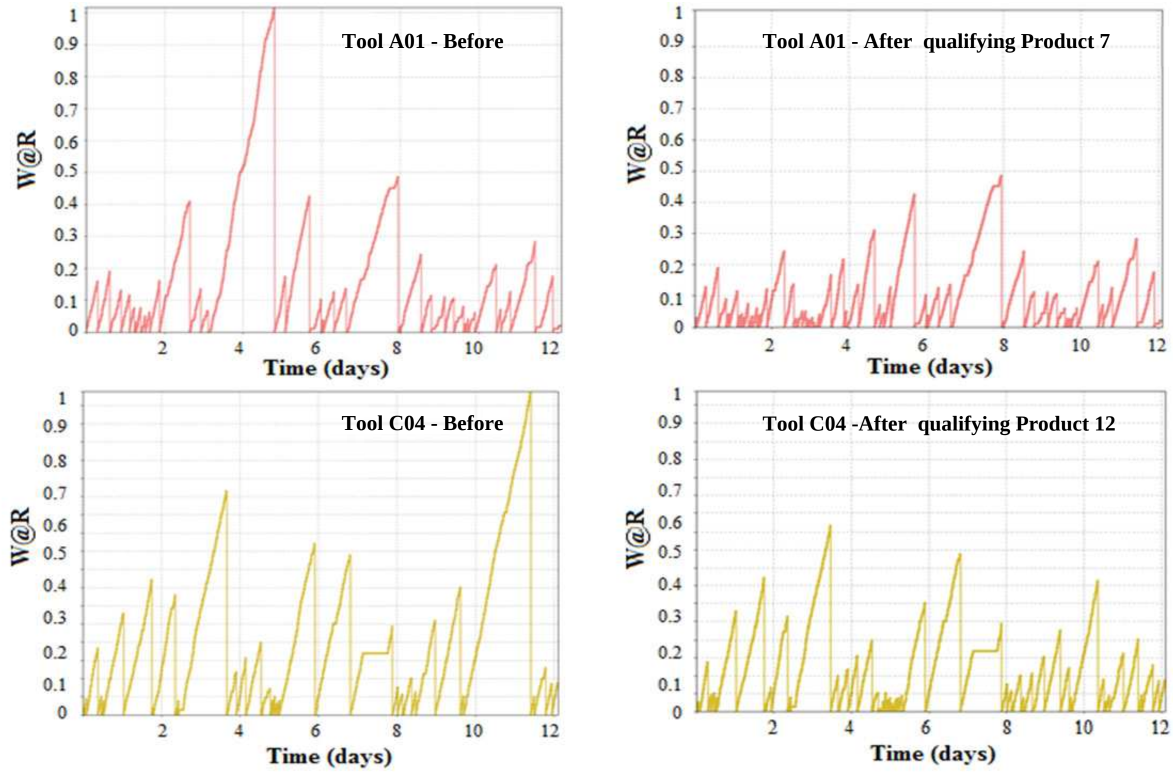

Figure 7: W@R for tools A01 and C04 before and after qualifying Products 7 and 12, respectively.

Qualifying new products offers opportunities to reduce the risk, but selecting the product that induces the most additional measures may not be the best alternative. Qualifying other products could be more interesting if their lots are processed on machines that are at risk. Looking at Table 2, it is interesting to see that, when qualifying Product 12 and although it has less measured lots than the other products, larger reductions for W@R Max of the process tools are obtained compared to the other products (except Product 7). For W@R Average, Product 12 has only 1% of difference when compared to Product 8, which is initially the second best option.

Table 2: Difference of global W@R reduction depending on the qualified product.

	Qualified products					
Indicator	**Product 7**	**Product 8**	**Product 9**	**Product 10**	**Product 11**	**Product 12**
Gain - W@R Max	20%	18%	16%	14%	13%	19%
Gain - W@R Average	29%	22%	22%	21%	20%	21%

When comparing the W@R evolution of all process tools between the real case and qualifying Product 7 in Figure 8, it can be seen that many tools reach the same W@R Max values without any changes; e.g. process tools A02, B04 and C03. However, the W@R Average is generally considerably reduced. It is interesting to see that, for process tools A02 and C03, the same W@R Max value is attained before and after qualifying products: W@R Max(A02) = 0.55 and W@R Max(C03) = 0.24. The behavior of their W@R Average is different, since the W@R Average of process tool A02 is almost divided by 2 (from 1 to 0.55), while the W@R Average of process tool C03 practically remains the same (from 0.19 to

0.16). In Figure 8, because the values are normalized, it is not possible to directly compare chart (a) and chart (b). Also, by definition, the W@R Average is always smaller than or equal to W@R Max.

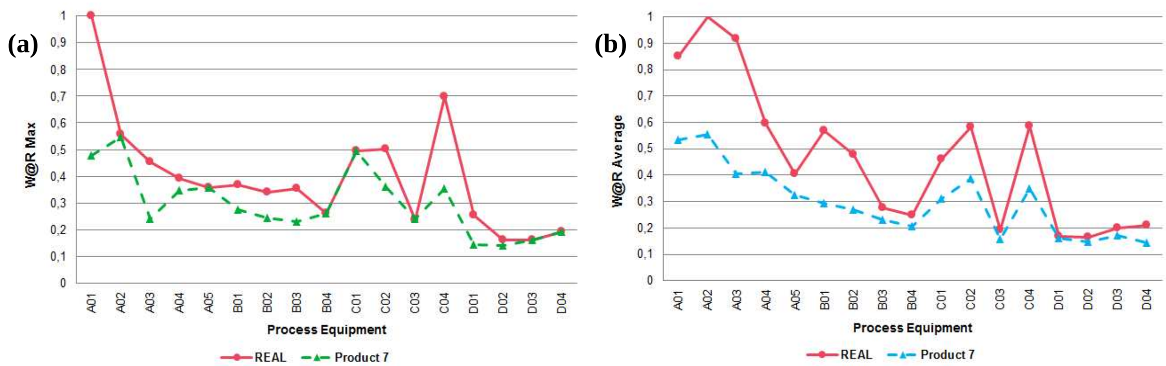

Figure 8: Comparison of W@R Max (a) and W@R Average (b) between real case and if Product 7 is qualified.

Hence, as it is shown through our simulations, by qualifying products, the risk is decreased but not all process tools are covered for all the cases, since even if the values of W@R Average are reduced, large maximum values are still reached. The next step is to qualify two products to reduce the risk even more.

4.4 Qualifying two products

As a starting point, only the combination of two products is considered due to the complexity for the workcenter to qualify products. To select products, the goal is to cover the largest number of process tools and to decrease the W@R values as much as possible. The best option is to select products 8 and 12 to qualify since it is the combination that leads to the largest W@R reduction for the 17 process tools. A comparison between the real case, qualifying product 8 and qualifying both products 8 and 12 is shown in Figure 9. The reduction is sometimes quite large, for example for process tool A03 (from 0.78 to 0.53) and, in other cases, less significant, for example for process tool D02 (from 0.14 to 0.12). This combination also covers process tools that were not improved with only one qualified product and leads to improvement on process tool A05 (from 0.36 to 0.28) and process tool B01 (from 0.37 to 0.18).

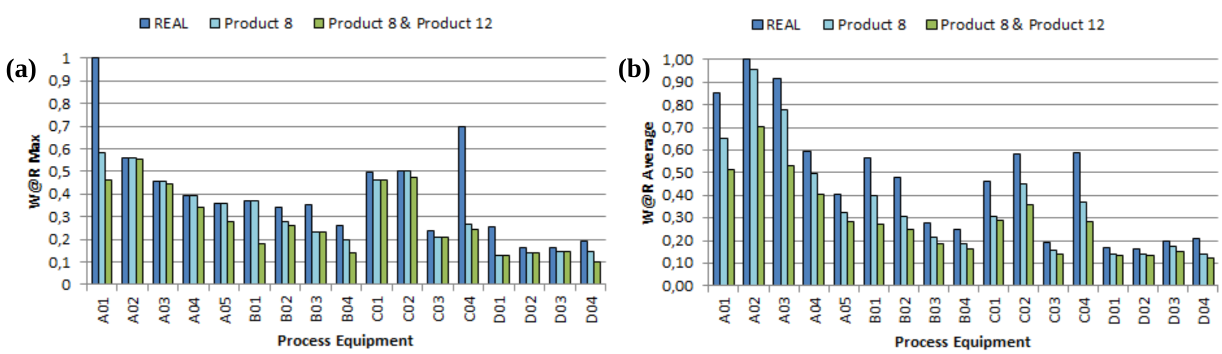

Figure 9: Comparison with qualifying products 8 and 12 for W@R Max (a) and W@R Average (b).

Due to the complexity for engineers to perform new qualifications, the goal is to qualify a little products as possible to cover the largest number of process tools and to reduce the risk much as possible. Qualifying more than two products could be considered if it brings significant gains in terms of W@R reduction.

5 CONCLUSION AND PERSPECTIVES

In this paper, a simulation model for a real workcenter in semiconductor manufacturing has been proposed. It has led us to better understand the current risk level, to detect several points to improve the current metrology process and to propose new risk reduction strategies. Our first approach has shown that qualifying new relevant products leads to significant risk reduction. The values of the Maximum W@R and the Average W@R are reduced, and the gain is larger when several products are qualified.

Our current research aims at finding a better method to select the products to qualify. We also want to implement new sampling techniques in the simulation model that select lots to measure at the right time that bring information, neither waiting too long before measuring a lot for a process tool nor performing a measure too early. An interesting perspective is to propose new scheduling and dispatching rules to assign lots to process tools with high risk. Finally, we would like to extend this work to other workcenters in semiconductor manufacturing facilities.

ACKNOWLEDGMENTS

This work has been carried out thanks to a collaboration between STMicroelectronics in Rousset (France) and the Ecole des Mines de Saint-Etienne (Centre of Microelectronics in Provence) in Gardanne (France). It is also supported by the ANRT (Association Nationale de la Recherche et de la Technologie) which has partially financed this work. This research is part of the project MAGE, financed by the "Programme d'Investissement d'Avenir" of the French Government.

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