Optimisation of the process control in a semiconductor company: model and case study of defectivity sampling

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Title: Process control releases without loss of information. Case study of defectivity sampling.

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Abstract: This paper studies the skip, under some assumptions, of a process control operation. The case of one tool, one enhanced buffer and one metrology tool of a monotonic parameter is analyzed. The paper presents in which circumstances a release of the control can happen, due to buffer behavior's. After presenting the industrial issue, the article goes through literature review. The article follows by presenting the model and steps toward industrial development. A demonstrator is then presented applied at a case study. A test over a 300mm wafer-fab data set shows serious improvements: around 10% of defectivity controls have been allowed to be skipped without any loss of information.

Keywords: Process Control, dynamic control plan, risk measurement, defectivity measurement .

1- Introduction:

The industrial problem underlying this works find its roots in front-end semiconductor facilities. Defectivity measurement (actually dust control) is performed over products and tools. After being manufactured, products can be oriented to control devices to release information they held about their cleanness. The result is used to qualify the production system and the product itself. Using data to monitor both products and processes is a common practice in statistical process control and acceptance controls.

Let's consider an oversimplified example: a dust control of a manufacturing device T like an etching tool. The level of dust, D, increases with the number of items produced. If a product is manufactured on the tool T, it adds dusts and can be contaminated by residues. It is controlled after being processed. T is considered as fouled if the level of D, measured on the product, is higher than a threshold limit $UL_{Dust.}$ In that case, the product is also labelled as dirty and either can be washed or have to be scrapped. Below this limit, product and tool are both considered as clean. Consider a sequence of 10 products P_1...P_{10}, produced with T and the associated sampling plan: to-control P_1 and P_{10}. P_1 is then produced and controlled. If P_1 is clean, then the production planning goes on. If it is measured as dirty, a clean operation has to be performed on T and P_1 (if possible). The production can be restarted. When P_{10} is controlled, if D doesn't reach UL_{Dust}, as dust has a property of accumulation throughout the production, one can say that P_2, P_3, P_4, P_5, P_6, P_7, P_8, P_9 are also clean. If P_{10} is dirty, then no conclusion can be inferred about previous productions.

Let's change the previous control plan for a 100% one. The travel between the manufacturing and control system can follow a stochastic law as illustrated Figure 1. B is made of: tool's output buffer, transportation queueing time and entrance buffer of the control tool C. The buffer B can behave in a range of stochastic laws. Following Figure 1, the, product P_1 is manufactured first and controlled in the fourth position due the buffer behavior. Some products can be controlled before products manufactured earlier. However, as the dust deposition is an increasing phenomena, it is understandable that if product P_4 has been released, product P_1 is also clean and it is not necessary to control it anymore.

This observation is at the basis of this article.

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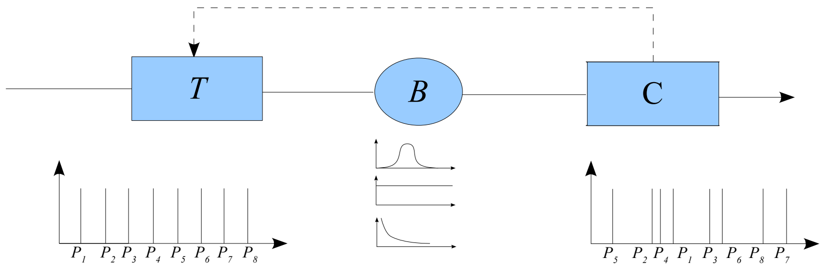


Figure 1: The production system

As in semiconductor industry, each pocket of productivity, easy to implement, is always welcome, being able to release controls, without loosing information can help at increasing the productivity in steady state mode and also ramp-up. This paper contributes then to move toward this goal by providing an algorithm to perform this task. A particular measure of operational risks at a tool level and the potential that a measurement has to reduce it has been introduced in order to be able to implement operationally this concept. A model of this case is presented revealing potential gains of this problem.

After this introduction the paper follows with a short literature review. A third part presents the model and associated development to be able to implement it operationally. A fourth part present case study and a small discussion.

2- Literature review:

The article of G. Spanos [1] introduces concepts of process control in Semiconductor industry. A detailed overview of process control tools and practices can also be found with the book of May and Spanos [2]. The work of Montgomery [3] is highly advised to understand concept of SPC, generalized in this industry. In order to design controls and adapt them throughout a technology lifecycle, design economic of control charts and adaptive control chart are two grounding fields of statistical control. The first one has been initiated by Duncan [4] in 1956. Major drawbacks have been pointed out, [5] toward this design mode and especially the lack of robustness of results. However, grounded with a true problem of balancing controls and their costs, developments have followed. The model of Lorenzen and Vance [6] is one of them and seems to be a milestone paper to the field as the development of Vommi and Stella [7]. A second development is the adaptation of control plan regarding events observed. Varying sampling interval, sampling frequency or changing of control limits are common actions taken as data are collected. The systematic analysis of this subject began with the publication of Reynolds et al [8]. They demonstrate that a two level of controls (sampling size, frequency, limits) is a better solution to control and detect faster issues while minimizing the cost of errors. Adaptive process control, have been reviewed by Taragas [9]. More recently, Magalhães, Costa, and Moura Neto present also a very clear overview of these technics [10] providing a key paper in this field. In industry, several authors focused on control adaptation and yield impact. Purdy [11] and Bousetta and Cross [12], present industrial development aiming the adaptive control of measurement, regarding yield evolutions and measurement capacity. The first paper presents a sampling strategy by counting the number of wafer passed on metrology tools. The second provide a mechanism to update control regarding process excursions.

All works that authors found about design economic and adaptive sampling where measured by the velocity of control chart detection. The reason why control chart have been settled is never retrieved in those papers. None of them is concerned with control release due to operation management control or risk evaluation.

The problem presented in introduction can be seen as a inspection re-allocation problem due to buffer's behavior and the variable monitored. The field of inspection allocation has been investigated since the publication of Lindsay and Bishop, in 1964 [13]. They studied a cost function per unit produced, taking in account the inspection cost and its location in the process. The minimum cost has been found for none inspection or entire batch inspected. Since their paper, several studies have been performed. Close to authors concern, in the field of Printed Circuit Board, Villalobos and al [14] present a flexible inspection systems for serial and multi-sage production systems. They provide an algorithm based on a Markov Chain model, to optimize global goal (like costs) and local constraints, like inspection tool availability. Verduzco and al. [15] present an interesting case of information based inspection allocation. They modeled a cost function taking into account the type I and II error linked at each measurement. They simulate their algorithm with a knapsack formulation. They yield that the information based solution reach better performances in term of classification errors that static inspections. Their paper has been a source of inspiration for authors as they introduce the fact that the control strategy can be modified based on its gain. John W. Bean, in his Master Thesis, in MIT [16] presents the development of an in-line, dynamic inspection plan, based on the probability of excursions, due to measurement. His work presents also the notion of material at risk (MAR) as each product between two samples can be impacted by defects. In order to be complete, in the field of inspection allocation, authors recommend the surveys of Raz [17]and Tang and Tang [18]. Close to the subject is development about automatic control and the position of sensors in the manufacturing process, in order to reduce uncertainty [19]. These models are tightly coupled with diagnosis approaches. In a nutshell, it is assumed that the more the process goes on, the more uncertainty is accumulated, and if it passes a threshold limit, a control has to be performed.

From these fields of researches, no papers have been found related to the release of measurement or inspection due to operation management.

As presented in introduction, measurement operations can be strongly influenced by operation management and especially way buffers production tool and control tool behave. Authors share point of view of Colledani and Tolio [20] that models of quality and quantity are rare in the literature. Hsu and Tapiero [21] pioneered this field by proposing a link between operation management and SPC control charts. S.B. Gershwin and J. Kim [22] and Colledani [23] presents academic investigations how quality and operations control can be linked. Especially, the paper of Colledani design the buffer size regarding quality and cycle time expectation. It is a model based on markov-chain model of a production system, allowing a multiple failure mode behavior's. However, none of these works models a possible release of measurements, due to operation management, nor models impact toward risk monitoring.

At the boundary of this research are risk management and production ramp-up. As it inspires authors, the literature goes through – very quickly- these domains.

During the production ramp-up of a transferred or a new technology being able to release control is crucial in order to be able to produce in time. we recommend to readers the industrial article of Bousetta and Cross [12] as an introduction to controls management practices, during ramp-up. We recommend also academic works about the subject: [24], [25], [26].

In the same time, almost all semiconductor industrials have to provide updated FMECA(Failure Mode Effects and Criticality Analysis) [27], [28], [29] about their tool, processes and products in order to ensure their customer, their ability to produce. These analyzes are about operational risk management, which can be defined as the elicitation, evaluation – often through ranking technics – mitigation and follow-up of “fearsome event, regarding stakes” [30]. A general survey of modern methodologies to master risks can be found in [31]. Measurements are performed -over products, processes and tools- in order to detect drifts and other possible operational risks occurrence. However very few articles truly link risk analysis and detection. Even in the adaptive controls field, risks are not explicitly mentioned. Only monitored process excursions (out of control events), which are precursors or consequences of operational risks, are monitored [16]. Pillet [32], pioneered the work of linking control plan at risks. An impact matrix has been presented linking risks and their elicitation at associated control. Bassetto [33] proposes an enterprise model joining risks elicitation, their evaluation and associated controls activities. The central idea, is that controls (charts, inspections...) are required due to the fact that tool, processes or product can have or produce failures. Each time one occurs, a revision of risks analysis has to be performed and associated control plans revised. The more risky it is, the more control have to be performed. This framework has been applied by Mili et al, [34] for defining maintenances priorities and improvement actions. Application of these models have been tested over a photolithography workshop. The major drawback of this research is that it remains at management level, without providing details about the manner to update controls, nor ensuring that no instabilities can emerged from this looped system. This issue has also be pointed out by JW Bean [16].

At joints of process control – or inspection-, risks management and operation management, research seems very promising, while surprisingly it has been timidly observed by authors in literature. Some researches are closest to the subject of this paper, however, authors haven't retrieved article about the purpose of this article. The release hasn't been studied yet and especially its impact in term of information. Of course, industrials can practice an adaptive control (especially defectivity one) without having published their methods other than a technical or internal report, unaccessible to authors. May be such practices can also be kept secret, as part of their operational excellence.

3- Model of the dynamic release of some sampling operations

The purpose of this part is to model and understand deeper the phenomenon presented in introduction in order to move toward a dynamic control plan, applied at defectivity measurement.

Assumption 1: The models under consideration is the case of one production tool, one buffer (made of the output buffer of the manufacturing tool, the transportation buffer – within the plant- the input buffer of the metrology tool) and one control device. This model over-simplify the reality but allow first developments.

Assumption 2: The problem of why products are re-scheduled into the buffer, is not taken into account in this article. Several factors are involved, especially, control plan, measurement capacity, transport plan, type of information attached at products. The product's waiting time between manufacturing operation and control operation, is only modeled with a random law ℓ.

Assumption 3: The metrology tool behave perfectly regarding the phenomenon observed over the product: error I and II are neglected in this first model. The measurement time is considered as constant: t_{Ctrl}. The information about product's cleanness is assumed to be immediately available after the measurement.

Assumption 4: The metrology is performed only over 1 parameter, which behaves in a monotonic manner exclusively with products. In the development below, it is considered as an increasing phenomenon as dust, grease, or painting deposition. The more goods are produced, the more contamination can happened for new products. When possible, decreasing phenomenon are presented in quotes.

Assumption 5: Data obtained on product variables allow to infer information about product functionality and about the way manufacturing tool behave. It is the case of contamination (dust, ionic, grease, etc.) for clean products like wafers or medical devices.

Assumption 6: The test, **C**, compares the value of a parameter named **Def** , measured on the i^{th} product named P_i, with a limit labelled UL_{Def} . A product is considered as non-defective if its measure is below (or higher) UL_{Def} (resp. LL_{Def}). **C** is a function from the product space in real **C**:{products}->Real.

Notations: k,j,i, three production indices / k<j<i

A clearing event is an action like a clean, a washing of the tool or every action that can requalify T for production. This includes maintenance actions and the dissipation of related effects (as Waddington effect for example).

Property 1: The consequence of the variable's monotonicity is that if a product P_i is tested and labelled as non-defective, then considering every products P_j, manufactured since the last non-defective product P_k, or the last clearing event, can be considered as correct. Demonstration : if there is a j / j<i & $C(P_j)>UL_{Def}$, by the monotonicity of the phenomenon monitored by C, $C(P_i)>C(P_j)>UL_{Def}$. Which is in contradiction with the measurement $C(P_i)<UL_{Def}$.- The demonstration follows the same pattern for a decreasing phenomenon with LL_{Def}.

If assumption 3 cannot be assumed, then this property has to be modified for a stochastic approach.

As a consequence of this property, if the information retrieved by the measurement is to compare these products toward UL_{Def}, (resp LL_{Def}) it is unnecessary to control them. The measurement can be skipped. When a product is scrutinized and considered as clean, products manufactured since the last qualification operation (maintenance or following a bad production detection) are also labelled as clean. At the opposite, if a product is measured as faulty or fouled, an investigation has to begin, every product before it can be contaminated. In a sceptic perspective, when a product is not measured, it joins the set of potentially bad products.

Mixed with a stochastic behavior of the buffer B (see Figure 1), P_i has a non null probability to be measured before P_j. The previous property can generates release of controls and by the way gains.

However these developments only point out possible improvement. Let's go further in the investigation of behavior and system performances [35], by introducing some complementary notations and assumptions.

Assumption 7: the model is made between two qualification actions or clearing events. The time elapsed between these two actions is named production cycle and noted PC. Indices of product within a Process Cycle, start at 1.

Assumption 8: For the sake of simplification, T produces goods in a regular manner every τ second, and follows a non stochastic behavior. We consider that $\tau \propto PC$. During PC, T produces PC/τ products.

Assumption 9: The control plan is set at 100%. Every manufactured product has to be measured.

Assumption 10: The probability that a i^{th} product is clean depends on the number of products produced before, since the last clearing event, and due to assumption 7, the beginning of the process cycle.
$p(P_i \text{ is clean}) \propto (1/\text{Number of items produced since last clearing event})^{\alpha}$, where α is a parameter
$p(P_i \text{ is clean}) \propto (1/i)^{\alpha}$ as a consequence of assumption 7.

The buffer B, follows a stochastic law, noted ℓ. The probability that a product goes out of B t_B time after being entered, is given by the formula : $p=\int_0^{tb}\ell(x)dx$.

Let's note: $t_C(P_i)$, the time where the information about P_i is available. $t_P(P_i)$ the time when P_i is manufactured and $t_B(P_i)$ the time elapses by P_i within the buffer B .

Property 1 can be transformed as follow:
$\forall(i,j)\in[1;PC/\tau]^2/j>i$, P_i can be released if and only if condition 1 and 2 are verified:

Condition 1: $t_C(P_j)\leq t_C(P_i)$
Condition 2: P_j is clean

Let's now evaluate the probability that these two conditions are true for a particular product.

Probability of Condition 1:

$t_P(P_i)=i*\tau$, $t_P(P_j)=j*\tau$

the buffer B behaves as a delay generator.
$t_C(P_i)=t_B(P_i)+t_P(P_i)= t_B(P_i)+i*\tau+t_{Ctrl}$
$t_C(P_j)=t_B(P_j)+t_P(P_j)= t_B(P_j)+j*\tau+t_{Ctrl}$

Condition 1 is verified $\Leftrightarrow t_C(P_j)\leq t_C(P_i) \Leftrightarrow t_{Ctrl}+t_B(P_j)+j*\tau\leq t_B(P_i)+i*\tau+t_{Ctrl} \Leftrightarrow t_B(P_j)\leq t_B(P_i)-\tau*(j-i)$

In term of probability that these event occurs for the product P_i,

Case 1: $\tau*(j-i)>t_B(P_i)$; (*) cannot be verified and $p(t_C(P_i)>t_C(P_j))=0$, P_i cannot be released for control,
Case 2: $\tau*(j-i)=t_B(P_i)$; $p(t_C(P_i)=t_C(P_j))=p(t_B(P_j)=0)$, $L(0)=\int_0^0 \ell(x)dx$.
Case 3: $\tau*(j-i)<t_B(P_i)$; the probability that the time elapse by (P_j) within the buffer is below $t_B(P_i)-\tau*(j-i) \Leftrightarrow \tau*(j-i)<t_B(P_i)$; $p(t_C(P_i)>t_C(P_j))\Leftrightarrow p(t_B(P_j))<\int_0^{tb(Pi)-\tau(j-i)}\ell(x)dx$

These 3 cases are valid for every product manufactured within the Process Cycle.

Probability of condition 2:
P_j has also to be clean. However, the last clearing event has to be anterior to i. In the contrary, nothing could be inferred from the cleanness of P_j .

$p(P_j \text{ is clean})\propto(1/\text{Number of items produced since last clearing event})^\alpha=(1/j)^\alpha$

Probability for a particular product P_i to verify condition 1 and condition 2, and to be released

Let's note $\mathcal{R}$, the set of products which can be released. During the production, $\mathcal{R}$ increases as products verify conditions 1 and 2. After a Process Cycle, $\mathcal{R}=\{ P_i/ i\in[1;PC/\tau], \exists j\in[1;PC/\tau]/j>i \ \& \ t_B(P_j)<\int_0^{tb(Pi)-\tau(j-i)}\ell(x)dx \ \& \ P_j \text{is clean}\}$.

A particular product P_i belongs to $\mathcal{R}$, if there is at least one product, produced after P_i that is measured before and if it is clean. These products can be P_{i+1} P_{i+2} … P_{k*}, where k* /

- the last product is produced within the Process Cycle : $k*\leq PC/\tau$
- the time elapse between P_i and P_{k*} is at the limit of P_i's waiting time within the buffer:
  - $t_B(P_i)>\tau(k*-i)$
  - $t_B(P_i)\leq\tau(k*+1-i)$

The probability that P_i belongs to $\mathcal{R} = p(P_i\in\mathcal{R})$
$\Leftrightarrow$ p([P_{i+1} reach C before P_i and $P_{i+1}$is clean] or [P_{i+2} reach C before P_i and P_{i+2} is clean]… or [P_{k*} reach C before P_i and P_{k*} is clean])

⇔ $\sum_{m=i+1}^{k^*} p(P_{i+m}$ reaches C before P_i and P_{i+m} is clean)
⇔ $\sum_{m=i+1}^{k^*} [p(t_B(P_m)<\int_0^{tb(Pi)-\tau(m-i)}\ell(x)dx))*p(P_{i+m}$ is clean)
In order to consider the equivalence, let's take the case where $p(P_j$ is clean$)=(1/j)^{\alpha}$
⇔ $\sum_{m=i+1}^{k^*} [p(t_B(P_m)<\int_0^{tb(Pi)-\tau(m-i)}\ell(x)dx))*(1/(i+m))^{\alpha}$

Algorithm:

This formulation is generic for every product being produced within a process cycle. In order to determine Card $\mathcal{R}$, this probability has to be evaluated for every product manufactured in a cycle. This sum, can be simulated knowing ℓ, $^{\alpha}$, and maintenance operations for some t_E . Of course, $t_B(P_i)$ are defined when the simulation reaches the i^{th} step. The algorithm is presented in Annex.

As the buffer behave in a stochastic manner, there is no reasons that this probability is systematically null, then Card $\mathcal{R}\geq 0$. As the initial control rate was 1 considering that Card $\mathcal{R}\geq 0$, the new sampling rate is $[1\text{-card } \mathcal{R}/(PC/\tau)]$.

Several problems are encountered at this level:

- To determine Card $\mathcal{R}$ in an exact manner.
- The evaluation of $p(P_i$ is clean) depends heavily on the way the risk monitored behave. Other probability function could have been chosen.

Illustrative example, based on the simulation

From the 1st product to the 1st Control. The control plan is set at 100%, $\alpha=0,5$

First Measurement:

Product	$t_B(P_i)$	$t_C(P_i)$	buffer output rank	Cumul prod since last Ctrl	Probability of being clean	Measurement	Result of Ctrl
1	57	58	6	1	1		
2	3	5	1	2	0,7=(1/2)^0.5	0,1	Clean
3	84	87	9				
4	87	91	10				
5	15	20	3				
6	73	79	7				
7	47	54	5				
8	9	17	2				
9	28	37	4				
10	76	86	8				

As a consequence, the measurement of the first product can be skipped.
The buffer's output is reordered for the second control.

Second Measurement

Product	$t_B(P_i)$	$t_C(P_i)$	buffer output rank	Cumul prod since last Ctrl	Probability of being clean	Measurement	Result of Ctrl
1	57	58	Skipped	1	Not computed		
2	3	5	Done	2	0,7=(1/2)^0.5	0,1	Clean
3	84	87	7	1		N/A	
4	87	91	8	2		N/A	
5	10	20	2	3		N/A	
6	73	79	5	4		N/A	
7	47	54	4	5		N/A	
8	9	17	1	6	0,35=(1/8)^0.5	0,3	Clean
9	28	37	3				
10	76	86	6				

The second measurement is declared as clean. This involves:

- Product 9 and 10 are moved from respectively from the 4th and 7th position to the 3 and 4th ones.
- Controls of product 3 to 7 are skipped

Third Measurement

Product	$t_B(P_i)$	$t_C(P_i)$buffer output rank	buffer output rank	Cumul prod since last Ctrl	Probability of being clean	Measurement	Result of Ctrl
1	57	58	Skipped	1			
2	3	5	Done	2	0,7=(1/2)^0.5	0,1	Clean
3	84	87	Skipped	1		N/A	
4	87	91	Skipped	2		N/A	
5	10	20	Skipped	3		N/A	
6	73	79	Skipped	4		N/A	
7	47	54	Skipped	5		N/A	
8	9	17	Done	6	0,35=(1/8)^0.5	0,3	Clean
9	28	37	1	1	0,31=(1/9)^0.5	0,6	Dirty
10	76	86	2		Not computed		

The 3rd measurement reveals a fouled tool. A cleaning action is performed and the process cycle is restarted. The probability of being clean is now (1/1)^0.5=1

Fourth Measurement

Product	$t_B(P_i)$	$t_C(P_i)$buffer output rank	buffer output rank	Cumul prod since last Ctrl	Probability of being clean	Measurement	Result of Ctrl
1	57	58	Skipped	1			
2	3	5	Done	2	0,7=(1/2)^0.5	0,1	Clean
3	84	87	Skipped	1		N/A	
4	87	91	Skipped	2		N/A	
5	10	20	Skipped	3		N/A	
6	73	79	Skipped	4		N/A	
7	47	54	Skipped	5		N/A	
8	9	17	Done	6	0,35=(1/8)^0.5	0,3	Clean
9	28	37	1	1	0,31=(1/9)^0.5	0,6	Dirty
10	76	86	1	1	1	0.2	Clean

In this example, 6 products have been skipped, over 10, without loss of information.

This part presents under some assumptions, that some controls can be skipped due to properties of the underlying phenomenon, without impacting information generation. A general formulation has been presented and a fake example illustrates the purpose. However in order to provide exact solutions, further investigations have to be continued. The probability presented in this part, is hardly obtains in real situations. It can be used for estimating a potential return on investment.

4- Toward an industrial application:

In order to operate properties presented above, another decision tool is introduced. As mentioned previously, while a product has not been measured, it is considered as suspect, and the tool also. A 100% sampling plan is often an utopia for process control activities. Sampling involves that some products are not controlled and can be revealed as dirty after having followed their production plan. A risk estimator is employed to ensure operational understanding sampling impact. At operation level, the main focus is on amount of product processed and potentially impacted by a fault. This estimator counts of number of potentially bad products. It measures the risk of impact. It is not an estimator of the behavior of the monitored phenomenon, in this case, the defectivity. The probability that a product has be contaminated is independent of this indicator. An illustration of this indicator is provided Figure 2. This counter is also known as Material At Risk [16], and named operationally wafers at risks.

This concept is threefold:

- From T point of view, each time it operates a product, a counter, named $IR(T)$ is increased. It is the number of products potentially impacted by the drift of the tool. In the remainder, it will also be named "risk indicator for the tool T". It depends of the number of products manufactured.
- From the product, when it is manufactured, it sees of the value of the risk at the time it is processed. $IR(P_i)=IR(T)_i$ Each time a product is controlled, due to assumption 5, this indicator evolves.
- Let's note $IR_r(P_i)$, the amount of $IR(T)$ reduction, associated at a measure and release of P_i. This measure is central to evaluate the information held by product.

With such definitions, there is a direct correspondence between information added by a product and risk taken by producing or controlling. This indicator has been and remains central to the communication with operational teams about the skipping action, as easier to manipulate than probabilities.

At time i, if the product is immediately controlled after being produced, if it is declare as clean, and if it is the first product to be measured since the last tool T qualification, then products produced before are released : $IR_r(P_i)=IR(T)_i$. Considering that a product P_i add to $IR(T)_i$, f(P_i) (typically f is a step 1 function, if tool operates one product per operation). $IR(T)_{i+1}=IR(T)_i+f(P_i)$ As $IR_r(P_{i+1})=IR(T)_{i+1}$, $IR_r(P_{i+1})=IR_r(P_i)+f(P_i)$. Until a measurement is performed values of risk reduction remain unchanged. By recurrence for the h^{th} product (implicitely produced at time h, and not notified here):

$$IR(T)_h=IR_r(P_h)=IR_r(P_i)+\sum_{z=i...h} f(P_z)=IR(T)_i+\sum_{z=i...h} f(P_z) .$$

This equation links a risk reduction potential at a time h, at the risk indicator of the tool at a predefined passed time i, in function of the production during i and h. While $P_{i,}$, hasn't been controlled, it enters in the risk reduction calculation for next products.

As each measurement makes the system evolves. Let's introduces some complementary notations :
$t_C(P_i)$ is noted k
The measurement of $P_{i,}$, is available at time k: C(P_i,k).

$(...)_{k-}$ notation for values just before the measurement at time k
$(...)_{k+}$ notation for values just after measurement at time k. For example:
$IR_r(P_i)_{k-}$ for $IR_r(P_i)$ before the measurement at time k,
$IR_r(P_i)_{k+}$ for $IR_r(P_i)$ just after the measurement at time *k*.

When a measurement occurs:
Case 1: If the product P_i is measured before product P_h, at time k (k/ k>h>i), and if C(P_i,k)<UL_{Def} it is declared as clean. This will modify the equation above.
$IR_r(P_i)_{k+}=0$ and $(\sum_{z=i...k} f(P_z))_{k-}=(\sum_{z=i...k} f(P_z))_{k+}$ remains unchanged as these product have been manufactured after P_i.

$$IR_r(P_h)_{k+}=0+(\sum_{z=i...k} f(P_z))_{k+}=(\sum_{z=i...k} f(P_z))_{k-}=IR_r(P_h)_{k-}-IR_r(P_i)_{k-}=(IR(T)_h)_{k-}-IR_r(P_i)_{k-}$$

The risk indicator is decreased of the value of $IR_r(P_i)_{k-}$ and $IR_r(P_h)_{k+}>0$.

This case is presented Figure 2.

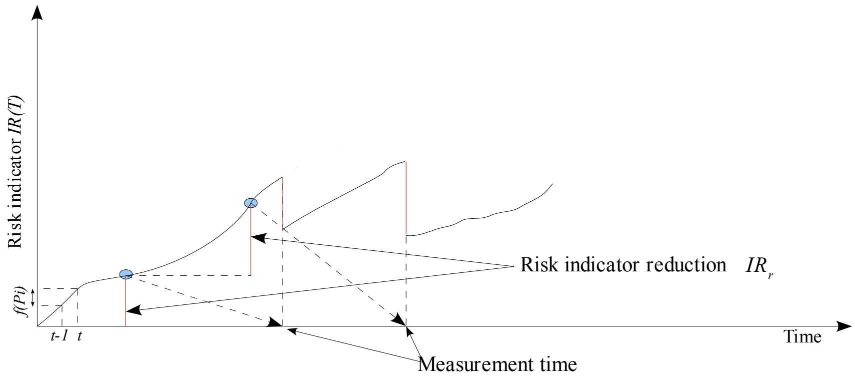


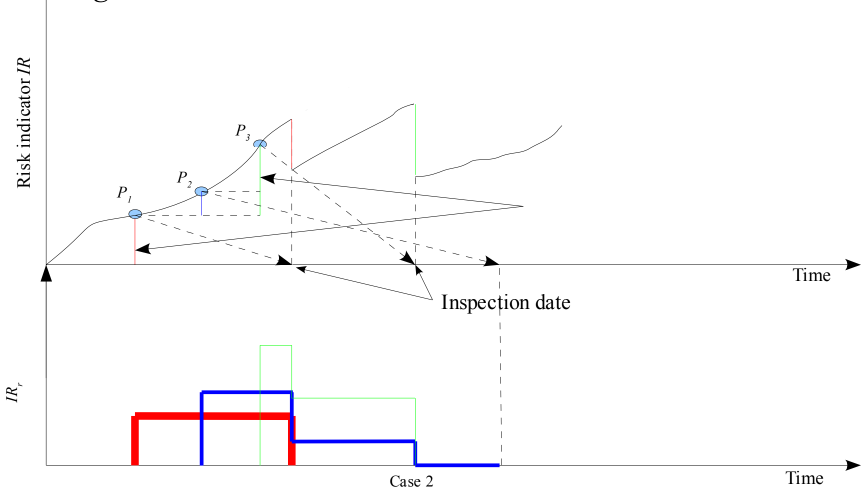
Figure 2: Risk indicator update when products order is not revised

Case 2: If the product P_h is measured first and $C(P_h,k)<UL_{Def}$. If P_h is declared “clean”, then due to the property demonstrated before, every product produced and not measured before can be released.

In the example of 10 products, the release of P_{10}, validates also $\{P_2...P_9\}$, 8 products. By the way, $IR(T)$ is decreased of 8. $IR_r(P_{10})_{10-}=8$. After this measurement, $IR_r(P_2)_{10+}=IR_r(P_3)_{10+}=...IR_r(P_9)_{10+}=0$.

$IR_r(P_i)_{k+}=0$ and $IR(T)_{k+}=0$ if h is the first product to be measured since the beginning of the production. This situation is presented Figure 3, where product 3 is measured before product 2, releasing it for production.

Figure 3: Risk reduction variation



The skip action: The action of case 2, for product P_i, is named : “skipping”. It is the drop of a control action, as the operation will not modify this indicator.

This indicator helps in clarifying the manner to operationalize previous property. Case one can be used to choose among a list of products to be measured, which one will induce the highest risk reduction. Case two induce the skip of a measurement.

The application

The case study takes place in a research an production semiconductor plant of STMicroelectronics in France. This facility is a Front-End Semiconductor 12' wafer fab. The case considers defectivity control, for etching tool. Defectivity is performed over several measurement devices, which will be assimilated at 1 single tool. The risk indicator is a counter of wafers, manufactured by the tool. Due to handling operations (automatic, or manual) and products priorities the time spent between the end of the manufacturing operation and the measurement one is very variable. It can happens that some lots produced in the afternoon are measured before lots produced in the morning, and the case 2, mentioned above seems to occurs frequently.

Case study assumptions: The case is limited at one manufacturing device, one defectivity tool. Products are assimilated here at lots of products, often made of 25 wafers. A lot intended for the defectivity carries only one information about the manufacturing tool which is the “wafer at risk reduction” noted IR_r .

A test computes IR in real time and perform the skip where possible has been realized central to this algorithm is the computation of condition 1 and condition 2 for each product observed. It uses real data from STMicroelectronics. It is presented Figure 4. In this figure, reader can see two x-axes for the time. The axe above is made of production's time. It is not linear and depend only of the times when products are manufactured. The second axe is the actual time. In this axe, measurements are represented with circles.

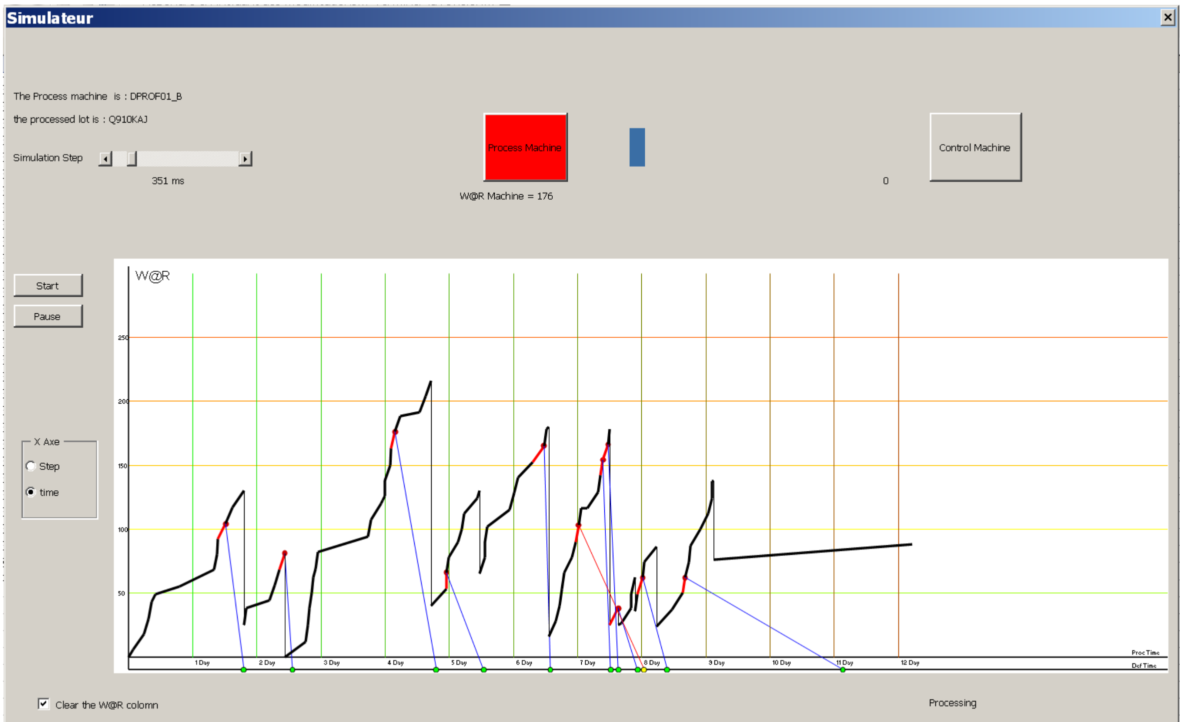


Figure 4: IR prototype

The interface, presented Figure 4, shows in real-time a graphical representation of the movement of lots in production, those waiting for the defectivity measurement and the evolution of IR .

In a first test, a data set has been prepared in order to run the algorithm. Over a 12 days period, one case allowed to be skipped has been introduced. Lots intended to be measured and their true entrance into the defectivity devices are presented in green. Lot intended to be skipped are flagged with a red line, as illustrated Figure 5. Lots actually skipped are represented with a yellow circle. The test has been successful. The lot fulfilling condition 1 and condition 2, has been identified and skipped as presented Figure 5.

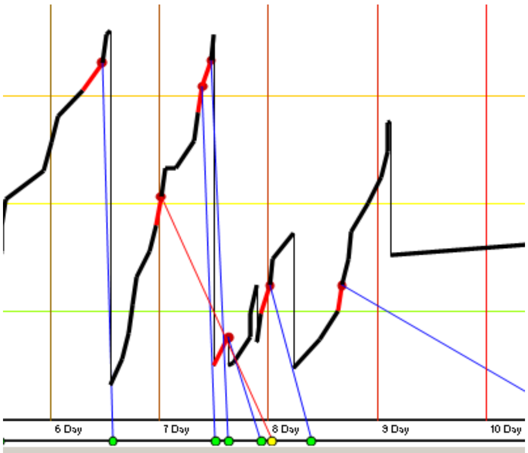


Figure 5: Zoom on case of skip

The algorithm has been performed over an history of more than 32,000 operations. The algorithm released an average of 10% of lots flagged for defectivity. Card Ꝛ/(PC/τ) =10%. This mean that 10% of these lots have been controlled, without adding any information and have cost in term of measurement capacity.

Small discussion:
The industrial application of the property demonstrated in this paper, is more concerned with the evaluation of the number of potentially infected wafers. However results are promizing as Card Ꝛ>0. The real case shows potential improvement and actual cost reduction of defectivity measurement.

There is then a deep interaction between manufacturing scheduling, and buffer behavior's leading at the release of controls, without losses of information.

Several development are ongoing:

- To move toward multiple manufacturing tools and use a mixed risk reduction indicator.
- The impact of the stochastic behavior of the buffer allows to release some controls, as they will not add any information regarding risks. However, regarding buffer's characteristics (mean time, variability, behavior's law, etc.) and regarding a specific production plan, the gain of capacity could be calculated.
- Finally, as information are linked at ramp-up development [36], with such a work we could identify delta between ramp-up previsions and real values dues to this loss of information.

Even if semiconductor industry generated the case study, every situation, following assumption presented in the model can also applied results.

5- Conclusion:
This paper presents a one tool, one buffer and one measurement device production system. It investigate a particular property of this system under 11 assumptions, in order to raise a class of problem and especially the variation of sampling rate, without the loss of information due to a stochastic behavior of the buffer. In order to operationalize this concept, a risk index is introduced

and a case study is presented in semiconductor manufacturing. The measurement is defectivity control. The article ends with openings, especially concerning the quantification of gains, in advance, by identifying buffer's behavior and its impact on capacity release.

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Annex: the simulation's algorithm

// Initialize variables
Initialize $E(t_E)$
Initialize PC
Initialize τ
Initialize α
Card $\mathcal{R}=0$

// computation of times and buffer order
For each product P_i manufactured within PC
    If P_i is flagged for control
        $t_B(P_i) \leftarrow \text{Randomize}(\ell)$
        $t_C(P_i) \leftarrow i+t_B(P_i)$
    Else
    End If
    $i \leftarrow i+1$
End For
Sort the output buffer of control, regarding $t_C(P_i)$ values

//computation of Card $\mathcal{R}$
For each product P_j within the control's stack (ordered from the 1st to be controlled to the last)
    Compute the probability that P_j is clean : $(1/(j-(E(t_E)+1)))^{\alpha}$
    and compare it with a randomized value.
    If it is higher,
        then the product is dirty, nothing can be inferred about previous product (if any)
        $E(t_E) \leftarrow j$
    Else
        It is clean, since the last clearing event, which occurs before it.
        List every products produced before and skip their controls.
        Card $\mathcal{R} \leftarrow$ lenght of this list.
    End If

End For

This algorithm works is not a real time. It is employed to evaluate the gain only.

Annex: the prototype algorithm

For each product produced

- Compute IR(T)
- Store time at which a cleaning event occurs
- Each time a measurement occurs, evaluate Ir(Pi), for product waiting for measurement since the last clearing event
  - If Ir(Pi)=0, then release the product.
  - Else let the product in the control buffer

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