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For Peer Review Only

## Optimization of the process control in a semiconductor company. Model and case study of defectivity sampling

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**Abstract:** This paper studies the skip, under some assumptions, of process control operations. The case of one tool, one enhanced buffer and one metrology tool of a monotonic parameter is analyzed. The paper presents circumstances in which control plan can be optimized due to buffer behavior's. After presenting the industrial issue of defectivity, 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 of defectivity sampling. A test over a 300mm wafer-fab data set shows serious improvements: around 35% of defectivity controls have been allowed to be skipped compared to the static sampling plan.

**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. Particles 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. These measurements are at the heart of defectivity and yield control (Kumar et al. 2006).

Let's consider an oversimplified example: a dust control of a manufacturing equipment T like an etching tool. The level of contamination, D, increases with the number of items produced. If a product is manufactured on the tool T, it adds particles 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 defective 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 defective, a clean operation has to be performed on T and  $P_1$  (if possible). If the cleaning is successful, the production can then 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 buffer 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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11 *Figure 1: The production system*  
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14 As in semiconductor industry, each pocket of productivity, easy to implement, is always welcome,  
15 being able to release controls, without losing information can help at increasing the productivity in  
16 steady state mode and also ramp-up. This paper contributes then to move toward this goal by  
17 providing an algorithm to perform this task. A particular measure of operational risks at a tool level  
18 and the potential that a measurement has to reduce it has been introduced in order to be able to  
19 implement operationally this concept. A model of this case is presented revealing potential gains of  
20 this problem.  
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23 After this introduction the paper follows with a short literature review. A third part presents the  
24 model and associated development to be able to implement it operationally. A fourth part present  
25 case study and a discussion.  
26

## 27 **2- Literature review:**

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30 The article of G. Spanos (Spanos 1991) introduces concepts of process control in  
31 Semiconductor industry. A detailed overview of process control tools and practices can also be  
32 found with the book of May and Spanos (May & Spanos 2006). The work of Montgomery  
33 (Montgomery 2004) is highly advised to understand concept of SPC, generalized in this industry. In  
34 order to design controls and adapt them throughout a technology lifecycle, design economic of  
35 control charts and adaptive control chart are two grounding fields of statistical control.  
36

37 The first one has been initiated by Duncan (Duncan 1956) in 1956. Major drawbacks have been  
38 pointed out, (Woodall 1986) toward this design mode and especially the lack of robustness of  
39 results. However, grounded with a true problem of balancing controls and their costs, developments  
40 have followed. As example, an historical article has been found about quality control skipping (John  
41 I.S. Hsu 1977). This paper is concerned with reducing the sample size and decreasing the control  
42 frequency, compared to a 100% or screening plan. It aims at identifying the right control frequency  
43 regarding a particular cost model. In the field of economic design of control charts, the model of  
44 Lorenzen and Vance (Lorenzen & Vance 1986) seems to be a milestone paper, as the development  
45 of Vommi and Stella (Vommi & Seetala 2007).  
46

47 A second development is the adaptation of control plan regarding events observed. Varying  
48 sampling interval, sampling frequency or changing of control limits are common actions taken as  
49 data are collected. The systematic analysis of this subject began with the publication of Reynolds et  
50 al (Reynolds Jr et al. 1988). They demonstrate that a two level of controls (sampling size,  
51 frequency, limits) is a better solution to control and detect faster issues while minimizing the cost of  
52 errors. Adaptive process control, have been reviewed by Taragas (Tagaras 1998). More recently,  
53 Magalhães, Costa, and Moura Neto present also a very clear overview of these technics (De  
54 Magalhães et al. 2009) providing a key paper in this field.  
55

56 In semiconductor industry, several authors focused on control adaptation, yield impact and risks.  
57 Based on an economic model which takes into account the reuse of SPC data during for yield and  
58 scraps investigations, Baud-Lavigne, Bassetto and Penz, (Baud-Lavigne et al. 2009) present how  
59 quality controls can be released due to learning curves. Purdy (M. Purdy 2007), Bousetta and Cross  
60 (Bousetta & Cross 2005), and Mouli and Scott (Mouli & Scott 2007) present industrial development

1  
2 aiming the adaptive control of measurement, regarding yield evolutions, measurement capacity and  
3 risks. The first paper, among those three, presents a sampling strategy by counting the number of  
4 wafer passed on metrology tools. The second provides a mechanism to update control regarding  
5 process excursions. The third presents a generic architecture to update control regarding risks  
6 encountered by the production. Their article presents an entire development, which seems to  
7 improve quality control performances. Key to their development is the concept of lot environment,  
8 they name *Partition* which is used to compute a risk index. However they do not provide further  
9 explanation of the manner they identify the risk index and its representativeness.

10  
11 All works that authors found about design economic and adaptive sampling are measured by  
12 the velocity of control chart detection. The reason why control charts have been settled is hardly or  
13 never retrieved in those papers. One present a grounded approach of adaptive quality controls based  
14 on yield improvement. One presents a generic approach to risk evaluation but no dot detail the  
15 reason why these risks are modeled so and consequences of such a model. None of them is  
16 concerned with control skip due to operation control.

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20 The problem presented in introduction can be seen as an inspection re-allocation problem  
21 due to buffer's behavior and the variable monitored. Inspection devices can be used to monitor other  
22 products than those defined in a static control plan, due to updated information about products.  
23 The field of inspection allocation has been investigated since the publication of Lindsay and  
24 Bishop, in 1964 (Lindsay & Bishop 1964). They studied a cost function per unit produced, taking in  
25 account the inspection cost and its location in the process. The minimum cost has been found for  
26 none inspection or entire batch inspected. Since their paper, several studies have been performed.  
27 Close to authors concern, in the field of Printed Circuit Board, Villalobos and al (Villalobos et al.  
28 1993) present a flexible inspection systems for serial and multi-stage production systems. They  
29 provide an algorithm based on a Markov Chain model, to optimize global goal (like costs) and local  
30 constraints, like inspection tool availability. Verduzco and al. (Verduzco et al. 2001) present an  
31 interesting case of information based inspection allocation. They modeled a cost function taking  
32 into account the type I and II error linked at each measurement. They simulate their algorithm with  
33 a knapsack formulation. They yield that the information based solution reach better performances in  
34 term of classification errors that static inspections. Their paper has been a source of inspiration for  
35 authors as they introduce the fact that the control strategy can be modified based on its gain. John  
36 W. Bean, in his Master Thesis, in MIT (Bean 1997) presents the development of an in-line, dynamic  
37 inspection plan, based on the probability of excursions, due to measurement. His work presents also  
38 the notion of material at risk (MAR) as each product between two samples can be impacted by  
39 defects. In order to be complete, in the field of inspection allocation, authors recommend the  
40 surveys of Raz (Tzvi Raz 1986) and Tang and Tang (K. Tang & J. Tang 1994). Close to the subject is  
41 development about automatic control and the position of sensors in the manufacturing process, in  
42 order to reduce uncertainty. These models are tightly coupled with diagnosis approaches of Zamai  
43 (ZAMAI 1997). It is assumed that the more the process goes on, the more uncertainty is  
44 accumulated, and if it passes a threshold limit, a control has to be performed.

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

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53 As presented in introduction, measurement operations can be strongly influenced by  
54 operation management and especially way buffers production tool and control tool behave. Authors  
55 share point of view of Colledani and Tolio (Colledani & Tolio 2009) that models of quality and  
56 quantity are rare in the literature. Hsu and Tapiero (Hsu & Tapiero 1989) pioneered this field by  
57 proposing a link between operation management and SPC control charts. S.B. Gershwin and J. Kim  
58 (S.B. Gershwin & J. Kim 2005) and Colledani (Colledani 2008) presents academic  
59 investigations how quality and operations control can be linked. Especially, the paper of Colledani  
60 design the buffer size regarding quality and cycle time expectation. It is 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 (Bousetta & Cross 2005) as an introduction to controls management practices, during ramp-up. We recommend also academic works about the subject: (Terwiesch & E. Bohn 2001), (Fine 1988), (Tapiero C. S. 1987).

In the same time, almost all semiconductor industrials have to provide updated FMECA(Failure Mode Effects and Criticality Analysis) (Chrysler Corporation, Ford Motor Company, General Motors Corporation 1993), (Department of defense 1980), (Villacourt 1992) 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” (De Choudens et al. 2000). A general survey of modern methodologies to master risks can be found in (Tixier et al. 2002). 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 (Bean 1997). Pillet (Pillet et al. 2007), pioneered the work of linking control plan at risks. An impact matrix has been presented linking risks and their elicitation at associated control. Ozouf, under the direction of Pillet, follow this path, by providing a deeper analysis of link between risk analyses type and control plan (Ozouf 2009). Bassetto (Samuel Bassetto 2005) 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 tools, processes or products 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, (Mili et al. 2009) for defining maintenance priorities and improvement actions. Application of these models have been tested over a photolithography workshop. This research remains at management level, and doesn't provide 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 (Bean 1997).

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 quality control release seems to be hardly studied yet and especially its impact in term of information. Of course, industrials can practice an adaptive control, regarding specific risks and their operations without having published their methods other than 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 quality control plan, applied at particle 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 allows 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, transportation, type of information belonging to products. The product's waiting time between manufacturing operation and control operation, is only modeled with a random law  $\ell$ .

*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 wafer'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 particles deposition, 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  $C: \{products\} \rightarrow Real$ .

*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 generate 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 (Li & Meerkov 2009), 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  $\tau$  second, and follows a non stochastic behavior. We consider that  $\tau \leq PC$ . During PC, T produces  $PC/\tau$  products.

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

*Assumption 10:* The probability that a  $i^{\text{th}}$  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  $\alpha$  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  $\ell$ . The probability that a product goes out of B  $t_B$  time after being entered, is given by the formula :  $p = \int_0^{t_B} \ell(x) dx$ .

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:

$\square (i, j) \square [1; PC/\tau]^2 / j > i$ ,  $P_i$  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  $\square t_C(P_j) \leq t_C(P_i) \square t_{Ctrl} + t_B(P_j) + j * \tau \leq t_B(P_i) + i * \tau + t_{Ctrl} \square t_B(P_j) \leq t_B(P_i) - \tau * (j - i)$

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  $t_B(P_i)$ -

$$\tau^{*(j-i)} \square \tau^{*(j-i)} < t_B(P_i) ; p(t_C(P_i) > t_C(P_j)) \square p(t_B(P_j) < \int_0^{t_B(P_i) - \tau^{*(j-i)}} \ell(x) dx$$

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  $P_j$ .

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

### Probability for a particular product $P_j$ 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,  $\mathcal{R} = \{ P_i / i \square [1; PC/\tau] \ \& \ \square j \square [1; PC/\tau] / j > i \ \& \ t_B(P_j) < \int_0^{t_B(P_i) - \tau^{*(j-i)}} \ell(x) dx \ \& \ P_j \text{ is clean} \}$ .

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  $P_{i+1} \ P_{i+2} \ \dots \ P_{k^*}$ , 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  $\mathcal{R} = p(P_i \square \mathcal{R})$

$\square p([P_{i+1} \text{ reach C before } P_i \text{ and } P_{i+1} \text{ is clean}] \text{ or } [P_{i+2} \text{ reach C before } P_i \text{ and } P_{i+2} \text{ is clean}] \dots \text{ or } [P_{k^*} \text{ reach C before } P_i \text{ and } P_{k^*} \text{ is clean}])$

$\square \sum_{m=i+1}^{k^*} p(P_{i+m} \text{ reaches C before } P_i \text{ and } P_{i+m} \text{ is clean})$

$\square \sum_{m=i+1}^{k^*} p(t_B(P_m) < \int_0^{t_B(P_i) - \tau^{*(m-i)}} \ell(x) dx) * p(P_{i+m} \text{ is clean})$

In order to consider the equivalence, let's take the case where  $p(P_j \text{ is clean}) = (1/j)^\alpha$

$\square \sum_{m=i+1}^{k^*} p(t_B(P_m) < \int_0^{t_B(P_i) - \tau^{*(m-i)}} \ell(x) dx) * (1/(i+m))^\alpha$

### 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  $\ell, \alpha$ . Of course,  $t_B(P_i)$  are defined when the simulation reaches the  $i^{\text{th}}$  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  $p(P_i \text{ is clean})$  depends heavily on the way the risk monitored behave. Other probability function could have been chosen.

### *Illustrative example, based on the simulation*

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

In this simulation,  $t_C(P_i)$  is known, leading at a ranking of product behind measurement tool.

The product 1 is produced at 1 and controlled at time 58. The product 2 is produced at 2 and

1  
2 controlled at time 5...It is clear that in this list, the second product is the first to be measured. Its  
3 probability of being clean follows the law of assumption 10, which leads at 0,7. As the  
4 measurement retrieve a value below this limit, the product is considered as clean. By the way, the  
5 first product is also declared as clean and skipped from control.  
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8 First Measurement - Table 1:  
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20 *Table 1. First measurement*  
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23 The buffer's output is reordered for the second control.  
24  
25

26 Second Measurement - Table 2

27 According to the fourth left-hand column, the second measurement occurs on the eighth product. Its  
28 probability of being clean equals 0,35. As the measurement retrieve 0,3, it is declared as clean and  
29 by the way its predecessors also. This involves:

- 30 • Product 9 and 10 are moved from respectively from the 4th and 7th position to the 3 and 4th  
31 ones.
- 32 • Controls of product 3 to 7 are skipped  
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45 Table 2. Second measurement  
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48 Third Measurement - Table 3

49 For this measurement, the 9<sup>th</sup> product is measured and its probability of being clean is 0,31. The  
50 measurement retrieve 0,6, which leads at a clearing event.

- 51 • Controls of product 3 to 7 are skipped  
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Table 3. Third measurement

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2 The 3<sup>rd</sup> measurement reveals a fouled tool. A cleaning action is performed and the process cycle is  
3 restarted. The probability of being clean is now  $(1/1)^{0.5}=1$   
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6 Fourth Measurement - Table 4

7 The fourth measurement is then made for a new cycle, as a clearing event occurs at the third  
8 measurement.  
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27 Table 4. Fourth measurement  
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30 In this example, 6 products have been skipped, over 10, without loss of information.  
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32  
33 This part presents under some assumptions, that some controls can be skipped due to properties of  
34 the underlying phenomenon, without impacting information generation. A general formulation has  
35 been presented and a fake example illustrates the purpose. However in order to provide exact  
36 solutions, further investigations have to be continued. The probability presented in this part, is  
37 hardly obtained in real situations. It can be used for estimating a potential return on investment.  
38

39  
40 **4- Toward an industrial application:**  
41

42 In order to operate properties presented above, another decision tool is introduced. As mentioned  
43 previously, while a product has not been measured, it is considered as suspect, and the tool also. A  
44 100% sampling plan is often an utopia for process control activities. Sampling involves that some  
45 products are not controlled and can be revealed as defective after having followed their production  
46 plan. A risk estimator is employed to ensure operational understanding sampling impact. At  
47 operation level, the main focus is on amount of product processed and potentially impacted by a  
48 fault. This estimator counts the number of potentially bad products. It measures the risk of impact.  
49 It is not an estimator of the behavior of the monitored phenomenon, in this case, the defectivity. The  
50 probability that a product has been contaminated is independent of this indicator. An illustration of  
51 this indicator is provided Figure 2. This counter is also known as Material At Risk (Bean 1997), and  
52 named operationally wafers at risks.  
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55  
56 This concept is threefold:  
57

- 58
- 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
- 59  
60

processed.  $IR_r[P_i] \cong IR_r[T]$  Each time a product is controlled, due to assumption 5, this indicator evolves.

- Let's note  $IR_r[P_i]$ , the amount of  $IR_r[T]$  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 declared as clean, and if it is the first product to be measured since the last tool  $T$  qualification, then products produced before are released :  $IR_r[P_i] \cong IR_r[T]$ . Considering that a product  $P_i$  add to  $IR_r[T]$ ,  $f(P_i)$  (typically  $f$  is a step 1 function, if tool operates one product per operation).  
 $IR_r[T_{i+1}] = IR_r[T_i] + f(P_i)$  As  $IR_r[P_{i+1}] \cong IR_r[T_{i+1}]$ ,  $IR_r[P_{i+1}] \cong IR_r[P_i] + f(P_i)$ . Until a measurement is performed values of risk reduction remain unchanged. By recurrence for the  $h^{th}$  product (implicately produced at time  $h$ , and not notified here):

$$IR_r[T_h] = IR_r[P_h] \cong IR_r[P_i] + \sum_{z=i..h} f(P_z) \cong IR_r[T_i] + \sum_{z=i..h} f(P_z)$$

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 evolve. Let's introduces some complementary notations :

$t_C(P_i)$  is noted  $k$

The measurement of  $P_i$ , is available at time  $k$ :  $C(P_i, k)$ .

$IR_r[P_i]_{k-}$  notation for values just before the measurement at time  $k$

$IR_r[P_i]_{k+}$  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  $k$  ( $k > h > i$ ), 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  $P_i$ .

$$IR_r[P_h]_{k+} = 0 + \sum_{z=i..k} f(P_z)_{k+} = \sum_{z=i..k} f(P_z)_{k-} = IR_r[P_h]_{k-} - IR_r[P_i]_{k-} = IR_r[T]_{h, k-} - IR_r[P_i]_{k-}$$

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,  $IR_{T_{k_{10}}}$  is decreased of 8.  $IR_{r_{P_{10}+10-}} = 8$ . After this measurement,  $IR_{r_{P_{2+10}}} = IR_{r_{P_{3+10}}} = \dots IR_{r_{P_{9+10}}} = 0$ .

$IR_{r_{P_{i+k}}} = 0$  and  $IR_{T_{k_{i}}}$  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 and discussion

The case study takes place in a research an production semiconductor plant of STMicroelectronics in France. This facility is a Front-End Semiconductor 300mm 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

1  
2 the tool. Due to handling operations (automatic, or manual) and products priorities the time spent  
3 between the end of the manufacturing operation and the measurement one is very variable. It can  
4 happens that some lots produced in the afternoon are measured before lots produced in the morning,  
5 and the case 2, mentioned above seems to occurs frequently.  
6

7  
8 *Case study assumptions:* The case is limited at one manufacturing device, one defectivity tool.  
9 Products are assimilated here at lots of products, often made of 25 wafers. A lot intended for the  
10 defectivity carries only one information about the manufacturing tool which is the “wafer at risk  
11 reduction” noted  $IR_r$  .  
12

13  
14 A test computes  $IR$  in real time and perform the skip where possible has been realized central to  
15 this algorithm is the computation of condition 1 and condition 2 for each product observed. It uses  
16 real data from STMicroelectronics. It is presented Figure 4. In this figure, reader can see two x-axes  
17 for the time. The axe above is made of production's time. It is not linear and depend only of the  
18 times when products are manufactured. The second axe is the actual time. In this axe, measurements  
19 are represented with circles.  
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22 *Figure 4: IR prototype*  
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46 The interface, presented Figure 4, shows in real-time a graphical representation of the movement of  
47 lots in production, those waiting for the defectivity measurement and the evolution of  $IR$  .  
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49  
50 In a first test, a data set has been prepared in order to run the algorithm. Over a 12 days period, one  
51 case allowed to be skipped has been introduced. Lots intended to be measured and their true  
52 entrance into measurement devices are presented in green. Lot intended to be skipped are flagged  
53 with a red line, as illustrated Figure 5. Lots actually skipped are represented with a white circle.  
54 The test has been successful. The lot fulfilling condition 1 and condition 2, has been identified and  
55 skipped as presented Figure 5.  
56

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58 *Figure 5: Zoom on case of skip*  
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1  
2 The algorithm has been run over 2 months of production. During that period, 14292 wafers have  
3 been flagged for defectivity measurement. The application of this algorithm showed that 5024  
4 wafers could have been released for production as they didn't add any new information. The  
5 algorithm released 35% of lots flagged for defectivity compared to the static sampling plan. Card  
6  $R/(PC/\tau) \approx 35\%$ . This mean that 35% of these lots have been controlled, without adding any  
7 information and have cost in term of measurement capacity, due to the fixed sampling.  
8  
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10 The industrial application of the property demonstrated in this paper, is more concerned with the  
11 evaluation of the number of potentially infected wafers. However results are promizing as Card  $R$  is  
12 far from 0. The real case shows potential improvement and actual cost reduction of defectivity  
13 measurement.  
14

15  
16 There is then a deep interaction between manufacturing scheduling, and buffer behavior's leading at  
17 the release of controls, without losses of information.  
18

19  
20 Particular development are ongoing:

- 21 • The impact of the stochastic behavior of the buffer allows to release some controls, as they  
22 will not add any information regarding risks. However, regarding buffer's characteristics  
23 (mean time, variability, behavior's law, etc.) and regarding a specific production plan, the  
24 gain of capacity could be calculated.  
25
- 26 • The impact of some assumption modifications as variable monotonicity and metrology tool  
27 behavior.  
28

29  
30 Even if semiconductor industry generated the case study, every situation, which fit assumptions  
31 presented for the model could apply the skip algorithm.  
32

### 33 **5- Conclusion:**

34 This paper presents a one tool, one buffer and one measurement device production system. It  
35 investigates a particular property of this system under 11 assumptions, in order to raise a class of  
36 problems and especially the variation of sampling rate, without the loss of information due to a  
37 stochastic behavior of the buffer. In order to operationalize this concept, a risk index is introduced  
38 and a case study is presented in a semiconductor manufacture. The measurement is defectivity  
39 control. The article ends with a special opening concerning the quantification of gains, in advance,  
40 by identifying buffer's behavior and its impact on capacity release.  
41

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44

45  
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47 "Implementing Manufacturing science solutions to increase equipment productivity and fab  
48 performance". IMPROVE is a JTI Project supported by the ENIAC Joint Undertaking, contract  
49 number: 12005.  
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**Annex: the simulation's algorithm***// Initialize variables*Initialize  $E(t_E)$ 

Initialize PC

Initialize  $\tau$ Initialize  $\alpha$ 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 1<sup>st</sup> 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  $\mathcal{R} \leftarrow$ length 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  $Ir(P_i)$ , for product waiting for measurement since the last clearing event
  - If  $Ir(P_i)=0$ , then release the product.
  - Else let the product in the control buffer

For Peer Review Only

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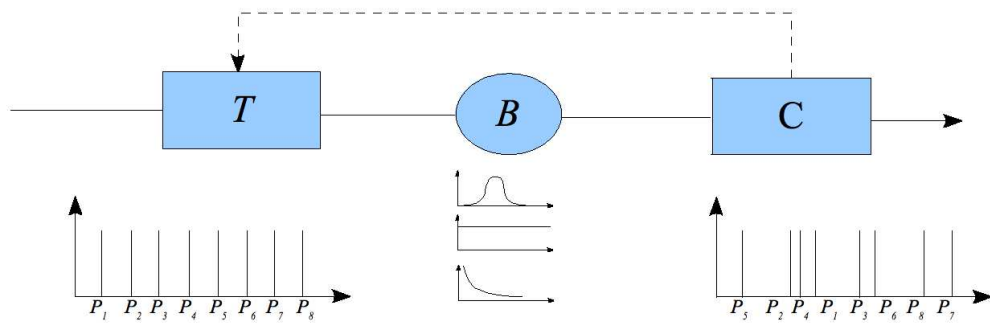
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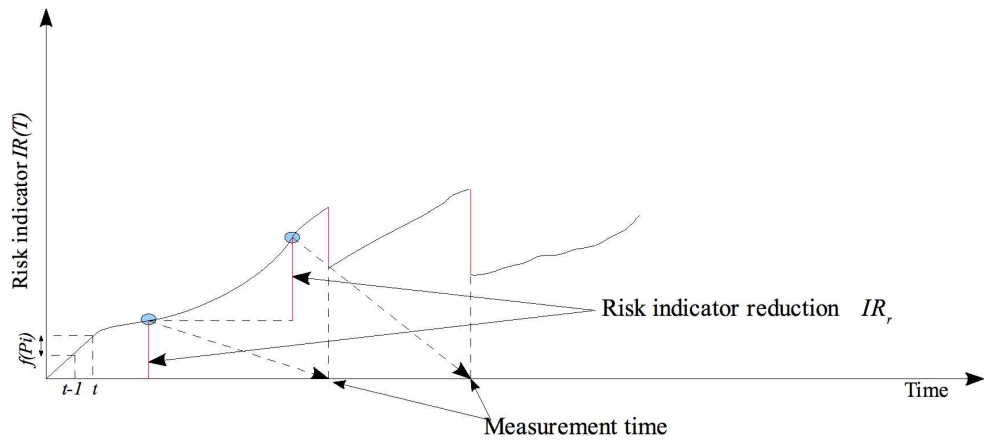
438x150mm (72 x 72 DPI)

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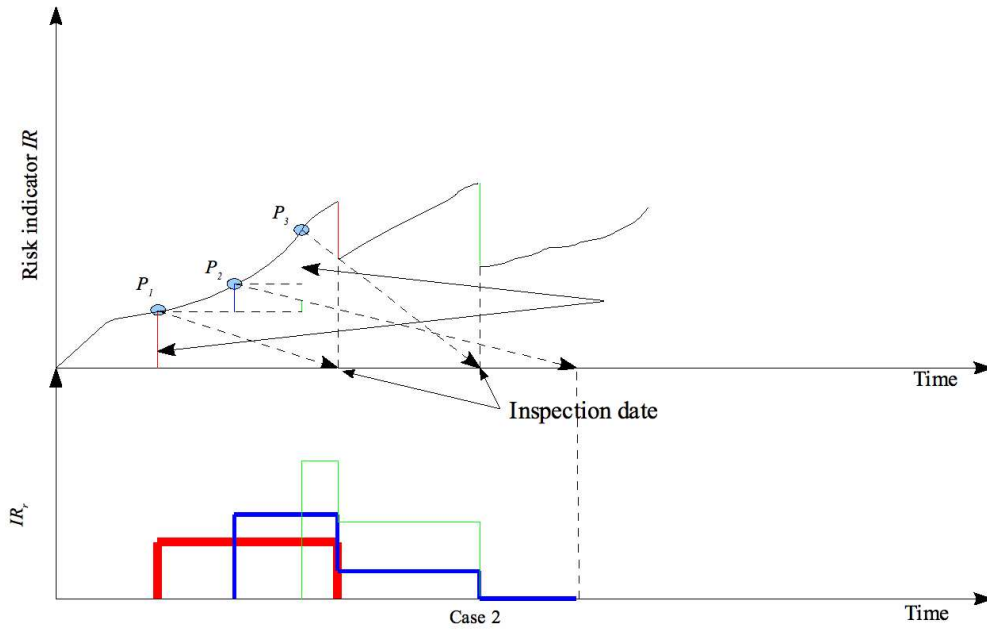


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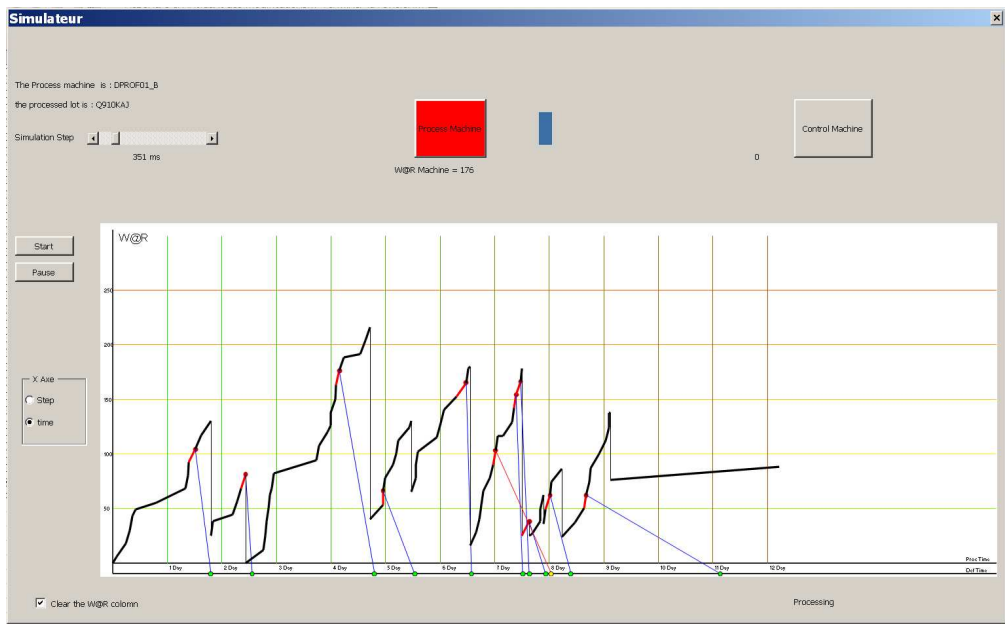


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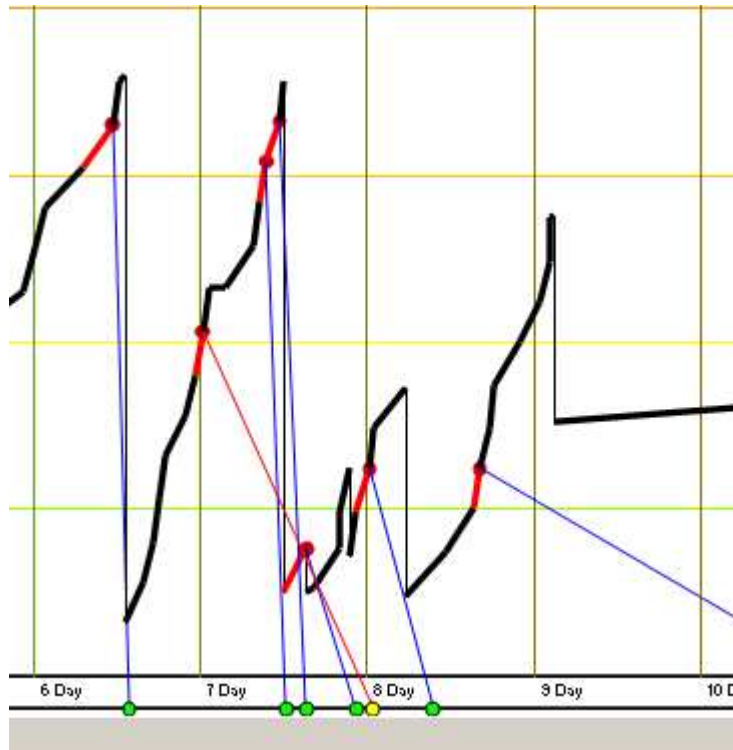
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323x199mm (120 x 120 DPI)

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77x78mm (120 x 120 DPI)

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