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THE ECONOMIC IMPACT OF METROLOGY METHODS IN SEMICONDUCTOR MANUFACTURING

by

Payman Jula

Memorandum No. UCB/ERL M01/22

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ELECTRONICS RESEARCH LABORATORY

College of Engineering
University of California, Berkeley
94720

The Economic Impact of Metrology Methods in Semiconductor Manufacturing

Payman Jula

Research Project

Submitted to the Department of Electrical Engineering and Computer Sciences, University of California at Berkeley, in partial satisfaction of the requirements for the degree of **Master of Science, Plan II.**

Approval for the Report and Comprehensive Examination:

Committee:

C. S. SPANOS

Professor Costas J. Spanos
Research Advisor

5/17/01

(Date)

* * * * * * *

Professor Robert C. Leachman
Second Reader

5/18/01

(Date)

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The Economic Impact of Metrology Methods in Semiconductor Manufacturing

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Abstract

Metrology is an essential part of advanced semiconductor manufacturing. It accelerates yield improvement and sustains yield performance at every stage in both new and mature processes. Appropriate metrology practices can reduce the cost and cycle-time of manufacturing through better characterization of tools and processes. Advances in metrology are needed to achieve difficult industry goals, such as smaller feature sizes and reduced time for introduction of new materials and processes for future technology. To achieve these goals, it is expected that metrology practices will migrate from offline to inline, and ultimately, to insitu.

Appropriate metrology models can assist the semiconductor manufacturers to assess the costs that drive their businesses and help them in formulating the right operational strategies. Economic models are needed to study the costs and benefits of introducing new metrology technologies and to compare alternative metrology practices.

To study the elements of cost in semiconductor manufacturing associated with different metrology tools and practices, several qualitative and quantitative models are presented in this document. Comparisons between insitu, inline and offline metrology systems are made. The cost components of the metrology methods are analyzed and discussed with respect to steady state process control as well as their effect on time to yield. Monte Carlo simulation models are used to study each system under different scenarios. Recommendations are proposed for best practices in each scenario.

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1. Introduction

Historically, semiconductor manufacturers rely on Statistical Process Control (SPC) techniques for maintaining the processes within prescribed specification limits. While semiconductor manufacturing has continued to pursue the ever-tightening specifications due to the well-known problems associated with the decreasing feature size, it has also become clear that there is a need for advanced-integrated process control. This approach requires a major shift in operational methods and requires the existence of complex, flexible architectures to meet the above requirements. New metrology tools are introduced as an essential part of these architectures.

Metrology accelerates yield improvement at every stage in both new and mature processes. Appropriate metrology practices can reduce the cost and cycle-time of manufacturing through better characterization of tools and processes. Advances in metrology are needed to achieve difficult industry goals, such as smaller feature sizes and reduced time for introduction of new materials and processes for future technology. To achieve these goals, it is expected that metrology practices will migrate from offline to inline, and finally, to insitu [1].

Unless convinced otherwise, manufacturers are usually reluctant to adopt major equipment and technology changes because of the short-term uncertainties, which arise during the introduction of new technologies. Appropriate metrology models assist the semiconductor manufacturers to assess the costs that drive their businesses and help them in formulating the right operational strategies. The ability to effectively identify cost drivers and manage cost reductions is a competitive advantage for any manufacturer. Therefore, accurate models are needed to study the costs/benefits of introducing new technologies and evaluate different practices. Toward this goal, this study introduces new analytical models to compare three different methods - offline, inline and insitu- in a litho/track system.

Although this study tries to address the economics of metrology systems in a general form, the examples and illustrations are developed for litho/track systems. Lithography steps are among the most crucial, and lithography tools are among the most expensive in semiconductor manufacturing. Most of the models offered in this document can easily be modified and extended to other equipment sets and metrology tools.

Figure 1.1 shows different metrology methods in a litho/track system in terms of the timing of the metrology operation in relation to the process. Wafers first enter the track system, where they go through some steps such as cleaning, coating and baking in preparation for the main lithography process (stepper), in which, small features are printed on the wafer. After the lithography, wafers go through other steps in the track system, such as baking and development. The qualities of the features carved during lithography (which in turn depends on the quality of the lithography process) have a direct effect on the quality of the final product. Therefore, we are interested in measuring and controlling the quality of the lithography step. The quality of the process* is represented by measuring certain quantities on the wafer, such as the critical dimension (CD) or the overlay.

* In this document, the main process (e.g. lithography), whose critical quantities are measured by the metrology tool, is called "the main process" or simply "the process".

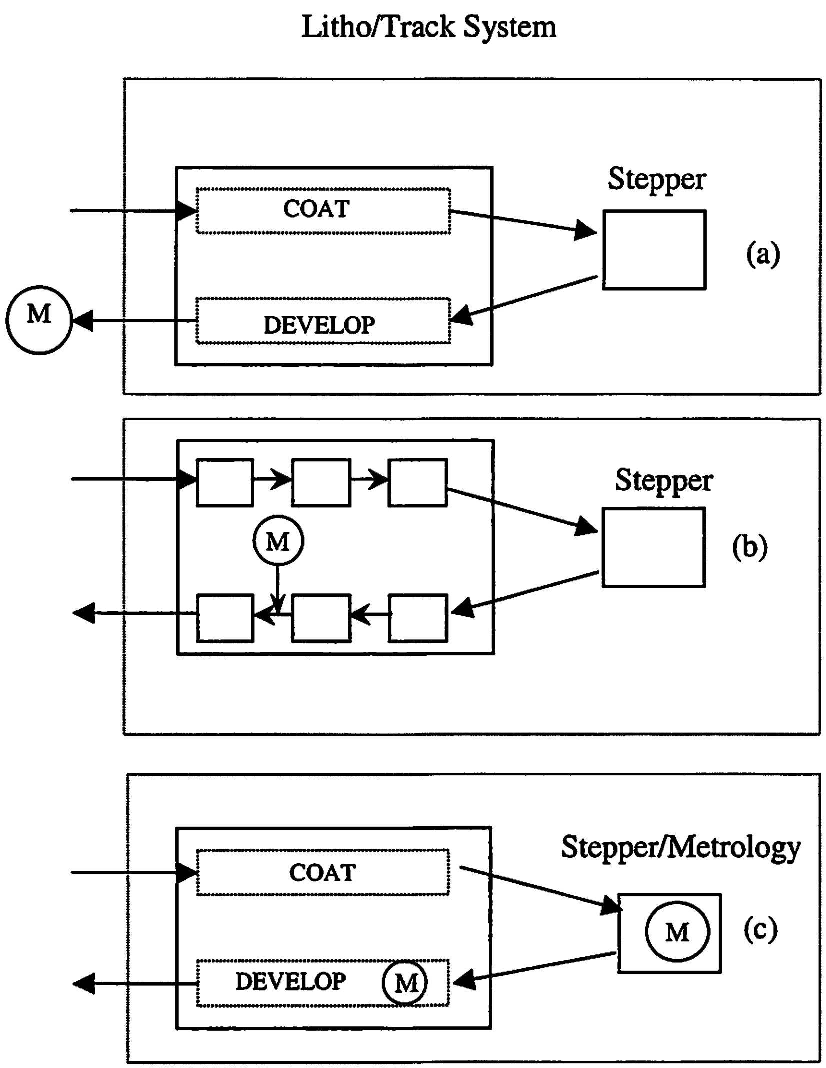

Figure 1.1. Different Metrology Methods Applied to a Litho/Track System: a) Offline, b) Inline, and c) Insitu. "M" indicates the position of the metrology tool.

Part (a) of Figure 1.1 shows an offline system. In this method, which has traditionally been practiced by semiconductor manufacturers, the metrology tool is located after the track system. Wafers are transported to the metrology tool by lots. Lots are then measured by the metrology tool with an appropriate sampling policy. Offline metrology tools are usually accurate and fast, but are also expensive and occupy significant clean room space.

Part (b) of Figure 1.1 shows an inline system. In this method, which has recently been commercialized in the lithography industry, the metrology tool is embedded in the track system. The metrology tool can either be mounted in the track system or be integrated with other processes such as baking. Wafers are processed within the metrology tool one at a time. Inline metrology tools occupy little footprint in the fab, and their accuracy and speed is generally inferior to off-line, but rapidly improving.

Part (c) of Figure 1.1 shows an insitu system. In this method, the metrology tool is fully integrated with the lithography tool. The measurements are done while the wafers are under process or shortly after the process is done. Insitu systems in lithography are under development and expected to be introduced with future generations of lithography tools.

To study the elements of cost in the above system, several qualitative and quantitative models are introduced in this document. In chapter 2, the major components of the costs and benefits for metrology practices are analyzed and two revenue and cost models are introduced. The effects of metrology methods on revenue during the steady state and the time to maturity are explained.

In chapter 3, Monte-Carlo simulation studies are conducted to compare different scenarios. First, the results of analytical model are compared to those of simulation model for a simple system. Then, the effects of yield and price structure, as well as control policies are examined in a series of scenarios. The results are presented and analyzed for each scenario. Recommendations are provided for each scenario and results are discussed. Conclusions and future avenues of study are explored in the last chapter.

2. Analytical Models of Metrology Methods

In general, since metrology operations are in series with the processes, they reduce the throughput and increase the Work In Process (WIP) and the cycle time. WIP inventory between a process step and the subsequent inspection is at risk if the process drifts to an undesirable state. Manufacturers have been trying to reduce these risks using different methods such as changing the sampling policies and send-ahead samples [2].

Simply reducing the number of samples may result in a better cycle time and WIP, but it has negative effects on the throughput of good products. Product yields at subsequent steps depend on the quality of information extracted from the metrology data. The quality of information generated from the metrology measurements can be partly characterized by parameters α_M and β_M. These parameters are the probabilities of errors involved in measuring a process. α_M, the type I error, is the probability of rejecting a good product or process. The type II error, β_M, on the other hand, shows the probability of accepting a bad product or process. The power of metrology, 1-β_M, in turn shows the probability of rejecting a process or product while it is indeed a bad product or process. Figure 2.1 shows the measurement risks involved in a metrology tool.

Classifications Based on the Measurement

		Good	Bad
Actual Process	Good	$1-\alpha_M$	α_M
	Bad	β_M	$1-\beta_M$

Figure 2.1. Probabilities of Process Misclassification

It is highly desirable to identify bad products passing through the metrology tool and detect the out of control state of the process as soon as possible. This can be achieved by tightening the acceptance criteria. If, however, these criteria are too tight, then good products may be rejected, or the system may unnecessarily be shutdown too often, resulting in production loss.

Another cause for production loss is the WIP between the process and the metrology tool. If the process drifts to an undesirable state, the process keeps manufacturing bad products until they are detected by the metrology tool. All the products in WIP, which have been produced since the process got out-of-control, need to be reworked or discarded. A Send-ahead (or look ahead) sample method eliminates the WIP risk but reduces the process throughput and utilization. In the send-ahead sample method, one or more wafers are processed and then submitted for measurement. The remaining wafers in the batch are processed after the measurements are complete, the results are released and the equipment is adjusted.

Therefore, it is also desirable to minimize the WIP in the system. Migrating from off-line to inline and insitu usually reduces the WIP. In other words, integrated inline and insitu metrology operation minimizes the WIP lost with little impact on utilization. But the feasibility of these approaches and the quality of data collected by inline and insitu tools, along with the price tag of these types of equipment should be considered in making a decision. These issues will be addressed in this chapter.

2.1. Overall Equipment Efficiency (OEE)

OEE is one of the most important metrics for measuring equipment performance. OEE is defined as the ratio of the theoretical time needed to produce salable wafers in a given period, divided by the total time in that period [4]. Theoretical time refers to the time required by a machine in perfect working order performing the process specification under ideal conditions. Figure 2.2 depicts the concept of OEE. Since in this study we are mainly interested in understanding the differences among metrology practices, we classify the losses in processing time to two main categories.

The first set of losses is associated with the metrology tool, its specifications, and the control policy chosen to detect and improve the bad process. The term "Bad process", in this document, refers to the process that is out of control and produces out-of-spec products; the products which are not conforming to the required specification set by the fab management. These specifications are those that are measured by the metrology tool. The crosshatched area between OEE and OEE* in Figure 2.2 shows the first set of losses. These losses are the focus of this study and will be explored later in this document.

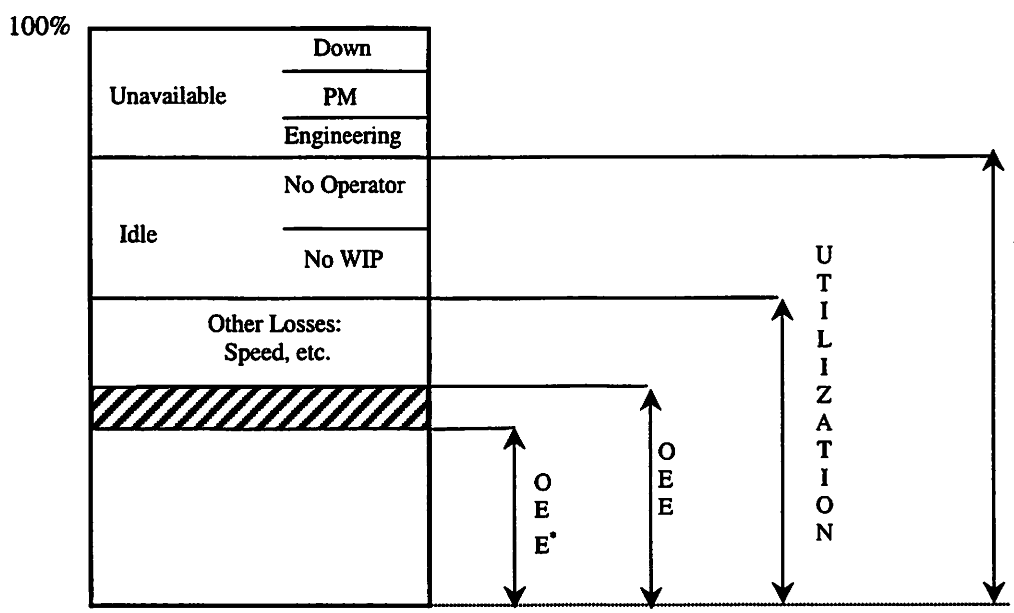

Figure 2.2. The Concept of Overall Equipment Effeciency (OEE)

The second set of losses contains any loss that is not captured in the first set. These losses are those that occur regardless of the type of metrology tool and the control policy. Any loss of production due to unavailability of machine, bad utilization of equipment and slow process belong to this category. The area between the OEE and 100% available time in Figure 2.2 shows this set of losses.

2.2. A Mathematical Model of Metrology Tools

In this section, we present a mathematical model that captures the behavior of a metrology tool. The model is developed to identify the main factors which are involved in the performance of a metrology tool corresponding to the main process. The relationship among these factors can be further studied by this model.

Assume the main process is up and in the "In Control" state for an exponential amount of time with the mean of *MTBF*, where *MTBF* is the Mean Time Between Failure of the process. The process goes to the "Out-of-Control" state and stays in this state until detected by the metrology tool. The time which is spent in the Out-of-Control state by the equipment is proportional to two factors; first, the time required for the results of the metrology tool to become ready, and second, the power of the metrology tool.

It is assumed that the equipment stays in the Out-of-Control state for an exponential amount of time with the rate of $(1-\beta)/ACTM$, where $(1-\beta)$ is the power of the metrology tool and *ACTM* is the Average Cycle Time to Metrology. *ACTM* is the response time from the metrology tool, which depends on the amount of WIP between the process and the metrology tool. After the metrology tool gives the signal that the process is out of control, the process is shut down and the repair starts.

It is assumed that the tool stays in this state, which is called "Failure Signal/Repair" state, for an exponential amount of time with the mean of *MTTR*, the Mean Time To Return. Because of the metrology type I error (α), there is a probability that the metrology tool generates a failure signal even though the process is in the good (in control) state. At any time interval h, the equipment in the good state may go to the "Failure Signal/Repair" state with the probability of (α*h). This can be justified by considering a balanced line, where the measurements depend on the time spent on the product. All notations in this chapter can be found in Appendix A.

The above system is a description of a Continuous-Time Markov Chain consisting of three states: namely, "In Control", "Out of Control" and "Failure Signal/Repair". Figure 2.3 shows this system.

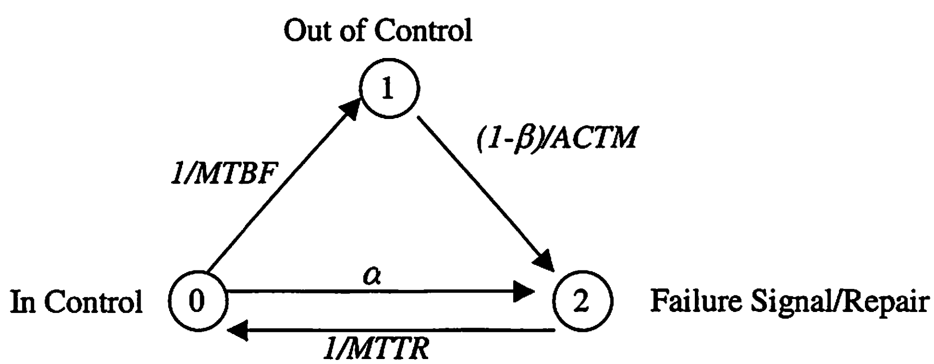

Figure 2.3. Continuous Time Markov Chain Model of a Metrology System

A Continuous Time Markov Chain is a class of probability models which include a stochastic process that moves from one state to another state in accordance with a (discrete-time) Markov chain. The amount of time spent in each state, before proceeding to the next state, is exponentially distributed. The amount of time the process spends in each state and the next state visited must be independent random variables. The long term probabilities that the process will be in a specific state, called limiting probabilities, can be obtained by solving this set of equations [3]:

$$\frac{P_0}{MTBF} + \alpha P_0 = \frac{P_2}{MTTR}$$

$$\frac{P_0}{MTBF} = \frac{(1-\beta)P_1}{ACTM} \qquad \text{(Eq. 1)}$$

$$\sum_n P_n = 1$$

This results in the following limiting probabilities.

$$P_0 = \frac{1}{1 + \frac{ACTM}{MTBF(1-\beta)} + MTTR(\alpha + \frac{1}{MTBF})} \qquad \text{(Eq. 2)}$$

$$P_1 = \frac{ACTM}{MTBF(1-\beta)[1 + \frac{ACTM}{MTBF(1-\beta)} + MTTR(\alpha + \frac{1}{MTBF})]} \qquad \text{(Eq. 3)}$$

where P_0 and P_1 are the long-term probabilities of the process being "Iin Control" and "Out of Control", respectively. The process under control produces acceptable products, while the out-of-control process produces bad products which should be reworked. The faster the out-of-control state is detected, the faster the process is calibrated; which limits the amount of required rework.

Therefore, the cost of a bad metrology practice is two fold. First, the cost due to the lost time of equipment (metrology and litho/track), which includes losses due to the expenses of investment in purchasing and installing the machines, maintenance, footprint, etc. The second cost element occurs because of WIP rework, resulting in material, energy and labor costs. These costs will further be studied in this chapter.

2.3. Revenue Models

Lets N_i denote the number of machines of type i that are installed in the factory. Ignoring the requirement that N_i must be an integer, Leachman *et al.* [4] have shown that N_i satisfies

$$(\frac{D}{Y_F})ThPT_i = N_i(OEE^*)(720) \qquad \text{(Eq. 4)}$$

where 720 is the number of hours in a month. The left hand side of this equation expresses the total machine-hours required to process $w=D/Y_F$ wafers per month; D is the designed output capacity and Y_F is the mature die yield. $ThPT_i$ is the total theoretical process time per wafer (expressed in hours) on equipment type i, considering all process steps performed by that equipment. The right hand side is the total machine hours that can be devoted to processing (at theoretical rates) considering the achieved equipment efficiency. The production rate per day can be expressed as

$$\frac{N_i(OEE_i^*)(24)}{ThPT_i} \qquad \text{(Eq. 5)}$$

Assuming a revenue of R_0 for each wafer for the current day, the total revenue per day in the near future can be calculated as

$$\frac{R_0(N_i)(OEE_i^*)(24)}{ThPT_i} \qquad \text{(Eq.6)}$$

Replacing the OEE^* with (P_0*OEE), where the P_0 is the long run probability of the process being in the good (in-control) state, will result in

$$\text{Revenue/Day} = \frac{R_0(N_i)(OEE_i)(24)}{ThPT_i} \cdot \frac{1}{1+\frac{ACTM}{MTBF(1-\beta)}+MTTR(\alpha+\frac{1}{MTBF})} \qquad \text{(Eq. 7)}$$

As expected, the revenue increases with the decline of α, β, *ACTM* and *MTTR* and decreases with the decline of *MTBF*.

Over the long run, where the price is declining according to a continuous discount factor of γ, the total revenue realized up to time H (expressed in days), assuming zero start-up and production delays, is expressed as

$$\int_0^H \frac{R_0(N_i)(OEE_i^*)(24)}{ThPT_i} e^{-\gamma t} dt = \frac{R_0(N_i)(OEE_i^*)(24)}{ThPT_i}(1 - \frac{1}{\gamma} e^{-\gamma H}) \qquad \text{(Eq. 8)}$$

2.3.1. The Effect of Metrology Tools on Ramp-Up

Up to this point, the behavior of metrology tools was considered in the mature and stable phase. However, as depicted in Figure 2.4, each process goes through three different phases: development phase where the process is first introduced, the ramp phase where the volume of production is increased, and the mature phase where the process sustains high volume production.

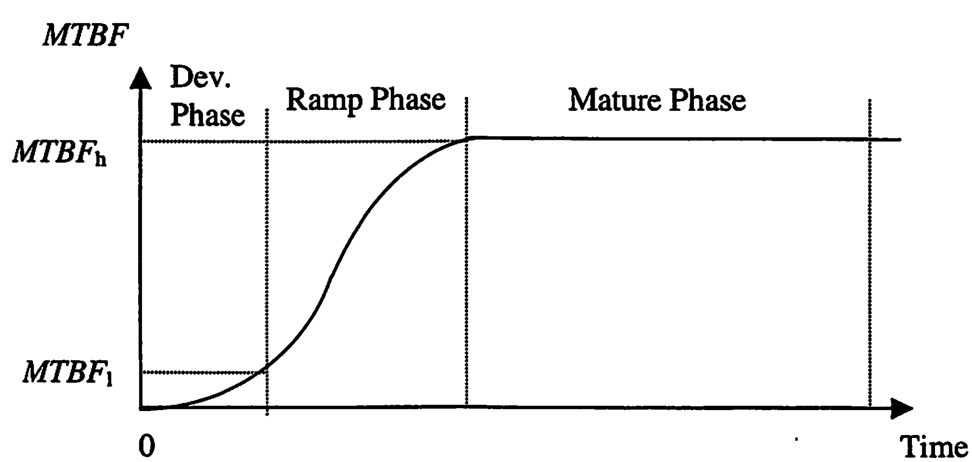

Figure 2.4. Different Phases of a Process Life Cycle

During the development phase, the equipment is installed and the appropriate recipe is applied. In this phase, the process usually does not produce any marketable product. Therefore, this phase is not in our interest. The process starts producing saleable products in the ramp phase. In the beginning of this phase, equipment fails more often. After some time, the process is calibrated, the rate of failures declines, and the process becomes mature.

Here, we are interested in studying the effect of the metrology tools on the ramp phase. For simplicity, we approximate the above curve with a step function, where the process has the average ($MTBF_{low}$) in the deveoplment and ramp phases and jumps to the mature phase ($MTBF_{high}$) at time T (Figure 2.5) .

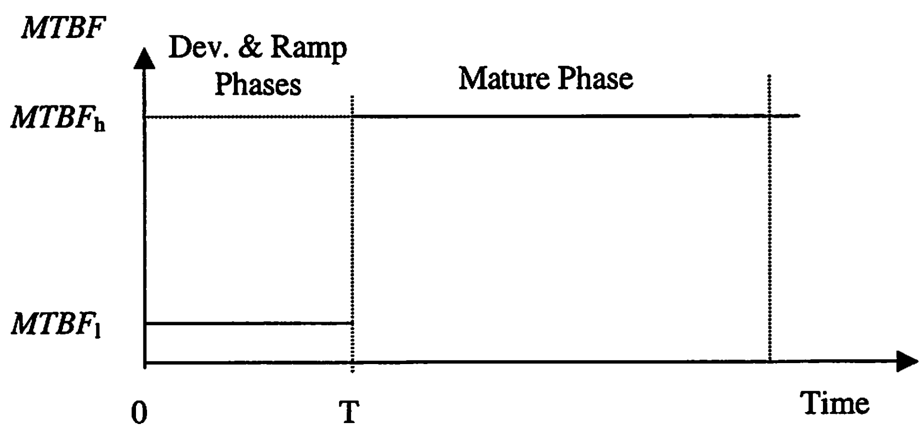

Figure 2.5. A Simplified Process Life Cycle

There are many factors which affect the duration of the ramp phase (T). Studying the behavior of these factors is beyond the scope of this study. However, it is known that the ramp-up duration, especially at lithography, depends on the knowledge and experience of the engineers working with the process. Part of the experience and knowledge comes from trial and error. Each equipment failure contributes to the knowledge about that equipment/recipe. Here, we assume the time to maturity is a function of the number of detected problems through time. The more problems are found, the more experienced the staff will become. Finally, after k number of trial and errors, the equipment goes to the mature state and the failure rate decreases. We are interested in finding the effect of metrology tools and the control policies on the value of T. Changes of T can then be translated to cost.

The number of equipment required is usually planned for the mature case; therefore, there is some lost revenue due to the unsatisfied demand in the development and ramp phases. Similar to Equation (4), the satisfied demand in development and ramp phase (D_R) follows the following equation.

$$(\frac{D_R}{Y_F})ThPT_i = (N_i)(OEE_i)(P_{0R})(720) \qquad \text{(Eq. 9)}$$

Here, the P_{0R} is the long-term probability of the process being under control during the development and ramp phases and follows an equation similar to Equation (2). All of the notations in this section are the specifications of the equipment in the development and ramp-up phases and are similar to those notations in the mature phase. Equations (4) and (9) result in

$$D_R = D\ (\frac{P_{0R}}{P_0}) \qquad \text{(Eq.10)}$$

and the lost demand per month during the development and ramp phases can be calculated as

$$D\ (1-\frac{P_{0R}}{P_0}) \qquad \text{(Eq.11)}$$

The duration and the quantity of the lost demand during the ramp period will result in lost revenue during this period. Figure 2.6 shows two different processes, one with the ramp-up time of T_2 and the other with the reduced ramp-up time of T_1. Later in this document it is shown how the area between these two curves can be translated into additional revenue due to the decrease of the development and ramp-up time.

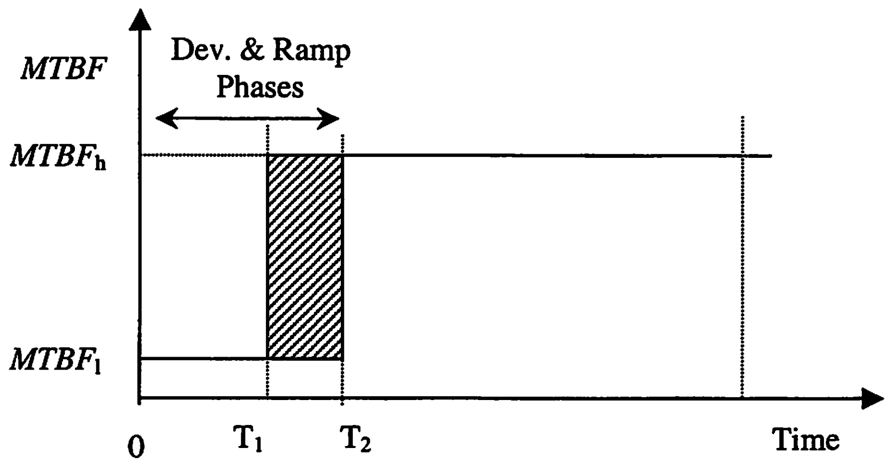

Figure 2.6. Reduction of Time to Maturity

Considering the Continuous Time Markov Chain model for the development and ramp phases, the transition rate from the Out-of-Control state to the Repair-Started state is

$$P_{1R}(1-\beta)\,/ACTM \qquad \text{(Eq. 12)}$$

Therefore, the expected value of T, the time for k number of repairs, is:

$$T = (k)(ACTM)\,/P_{1R}(1-\beta) \qquad \text{(Eq. 13)}$$

The total possible revenue during the development and ramp phases, assuming all demands are satisfied, can be expressed as

$$\int_0^T R_0 e^{-\gamma t} \frac{D}{30} dt \qquad \text{(Eq. 14)}$$

Here, γ is the continuous discount factor for the exponentially declining price. The lost revenue can be calculated as

$$\int_0^T R_0 e^{-\gamma t} \frac{D}{30}(1-\frac{P_{0R}}{P_0})dt \qquad \text{(Eq. 15)}$$

The difference of the total lost revenue can be calculated as

$$\Delta R = R_0(\frac{D}{30})(\frac{P_{0R}}{P_0})(\frac{1-e^{-\gamma T}}{\gamma})$$

$$= R_0(\frac{D}{30})(\frac{P_{0R}}{P_0})(\frac{1-e^{-\gamma\frac{k.ACTM}{P_{1R}(1-\beta)}}}{\gamma}) \qquad \text{(Eq. 16)}$$

2.3.2. Comprehensive Revenue Model

The comprehensive revenue model consists of the combined revenue obtained in the ramp phase and the mature phase. The total revenue obtained in the ramp phase can be expressed as

$$(\frac{R_0}{\gamma})(\frac{D}{30})(\frac{P_{0R}}{P_0})e^{-\gamma\frac{k.ACTM}{P_{1R}(1-\beta)}} \qquad \text{(Eq. 17)}$$

Given the duration of the mature phase, the total revenue obtained in the mature phase can be calculated by Equation (8). The combination of Equations (8) and (18) should be considered in selecting the metrology setup.

The revenue models are more tailored towards the marketing department's needs versus the manufacturing expenses. In other words, they only consider the incoming cash flow to the company through sales. These models do not consider the outgoing cash flow and the expenses of the company. What if a metrology tool improves revenue, but the price of investment is high? How about the maintenance expenses and labor costs associated with each metrology system? These issues will be addressed by another model, called the cost model, in the following section.

2.4. The Cost Model of Metrology Methods

According to Leachman *et al.* [4], total fab expenses per year (*EPY*) can be captured by the total costs due to the machines, the number of wafers started and the fixed costs as

$$EPY = EPY(Machines) + EPY(Wafer\ started) + Fixed\,Cost$$

Mathematically, *EPY* can be captured by the following equation

$$\begin{aligned} EPY = \sum_i (Ce_i + Le_i + Se_i)\frac{(D)(ThPT_i)}{(Y_F)(OEE^*)(720)} \\ + (Lw + Mw + Sw)(12)w + (Lf + Sf) \end{aligned} \qquad \text{(Eq. 18)}$$

where Ce_i is the amortized purchase and installation cost plus the annual maintenance cost per machine of equipment type i (expressed in dollars)

Le_i = The portion of labor cost (wages, salaries, benefits) that is proportional to the number of machines of equipment type i (expressed in dollars).

Se_i = Occupancy cost plus amortized capital cost for factory facilities and infrastructure per machine of equipment type i (expressed in dollars). This is the portion of total facility and infrastructure cost that is proportional to the floor space allocated per machine of equipment type i.

Lw = The portion of labor cost that is proportional to the number of wafers started, per wafer start (expressed in dollars)

Mw = Material cost, assumed to be proportional to the number of wafers started, per wafer start (expressed in dollars)

Lf = Fixed labor cost, i.e. the portion of labor cost that is independent of wafer start volume and the installed equipment (expressed in dollars).

Sw = The portion of total facility and infrastructure cost that is proportional to the number of wafers started, per wafer started (expressed in dollars).

Sf = Fixed space cost, i.e. the portion of total facility and infrastructure cost that is independent of wafer volume and installed equipment (expressed in dollars).

Introducing metrology to a litho/track system will affect the time that the system spends in producing revenue products. This change can be captured by the overall equipment efficiency (OEE) of the litho/track system. The OEE is reduced by the factor P_0, the probability of being in the in-control state as presented in Equation (2). The total expenses of the machines per year can then be expressed as:

$$EPY(Machines) =$$

$$(Ce_{litho} + Le_{litho} + Se_{litho})\frac{(D)(ThPT_{litho})[1 + \frac{ACTM}{MTBF(1-\beta)} + MTTR(\alpha + \frac{1}{MTBF})]}{(Y_F)(OEE_{litho})(720)}$$

$$+ (Ce_{met} + Le_{met} + Se_{met})N_{met} + \sum_{i \in other}(Ce_i + Le_i + Se_i)\frac{(D)(ThPT_i)}{(Y_F)(OEE_i)(720)} \qquad \text{(Eq. 19)}$$

The "*litho*" subscript represents the lithography system, which includes the exposure unit and the track line. The first term in Equation (19) captures the effect of metrology in lithography costs through its effective processing time. The second term is the cost associated with the purchase, maintenance and the footprint of metrology devices. The third term captures the rest of the expenses in the fab.

As discussed earlier, different metrology methods generate different amount of WIP and rework. The rework consumes materials, energy and labor. Furthermore, the mask life, which is considered dependent on the number of exposures, causes the expenses to increase in proportion to the number of rework.

Similar to Equation (4), according to our Continuous Markov Chain model, the total out-of-control machine-hours spent processing w_r products will be:

$$(w_r)(ThPT_i) = (\frac{P_1}{P_0})(N_i)(OEE_i^*)(720) \qquad \text{(Eq. 20)}$$

Considering Equations (2), (3), (4) and (20), the total number of reworked wafers per month can be calculated based on the monthly production rate as

$$w_r = (\frac{ACTM}{(1-\beta)MTBF})(\frac{D}{Y_F}) \qquad \text{(Eq. 21)}$$

The fab total expense per year due to the number of wafers started includes two terms. The first term captures the expenses due to the reworked wafers in lithography steps. These expenses reflect material costs, energy, labor and masks. The second term includes all expenses that are functions of the number of wafers started. All the rework done on the other equipment sets (except lithography) are assumed to belong to this category. Therefore, the total expenses per year due to the number of wafer starts can be expressed as

$$EPY(Wafer\,started) =$$

$$(Lw_r + Mw_r + Sw_r)(12)\frac{(ACTM)}{MTBF(1-\beta)}\frac{D}{Y_F} + (Lw + Mw + Sw)(12)w \qquad \text{(Eq. 22)}$$

The constant terms of Equation (18), *Lf* and *Sf*, are assumed to remain unchanged after introducing different metrology methods.The difference between metrology methods can be calculated according to Equations (19) and (22). This difference can be presented as:

$$\Delta EPY = (Ce_{litho} + Le_{litho} + Se_{litho}) \frac{(D)(ThPT_{litho})[1 + \frac{ACTM}{MTBF(1-\beta)} + MTTR(\alpha + \frac{1}{MTBF})]}{(Y_F)(OEE_{litho})(720)}$$

$$+ (Lw_r + Mw_r + Sw_r)(12) \frac{(ACTM)}{MTBF(1-\beta)} \frac{D}{Y_F} + (Ce_{met} + Le_{met} + Se_{met}) N_{met} \qquad \text{(Eq. 23)}$$

To choose the best metrology method, manufacturers should consider the elements involved in Equation (23). All the costs associated with acquiring, installing and maintaining the litho/track tools should be considered. Special attention should be given to the quality of information extracted from the metrology tools. The failure rate, ease of repair and the position of metrology tool in the system should also be considered.

2.5. Discussion

In this chapter, two models were introduced. The revenue model emphasizes the incoming cash flow and is tailored towards the marketing needs. The cost model, on the other hand, emphasizes the expenses of the fab and is designed to address the manufacturing needs.

These models assist managers in deciding the best metrology strategies. They give an understanding of the elements involved in the decision-making process and help the decision makers to grasp the relationships among these factors. These models are based on some simplifying assumptions and their accuracy should be verified in any real-world decision making process. It is very difficult to capture all the factors involved in a real world problem in a simple model. Manufacturers mostly rely on simulation approaches to assist them in understanding the behavior of the processes and in selecting the best operating practices. The next chapter will explore the behavior of metrology methods in more complex environments with the help of Monte-Carlo simulations.

3. Monte-Carlo Simulation Models of Metrology Methods

In Chapter 2 several analytical models were presented for litho/track systems based on some simplifying assumptions. These models help manufacturers identify some of the important factors involved in the economics of the metrology systems. These models can further be used to understand the relationship among these factors. There is still a need to address the issues involved in more complex systems which arise in industrial environments. Appropriate models can predict the behavior of these systems under different scenarios. These models will help the decision makers in selecting the best practices in different environments. However, it is very difficult to capture the behavior of these complex systems with closed-form mathematical models, similar to those presented in the previous chapter. As an alternative, Monte-Carlo (MC) simulation models are developed in this chapter and used to study the behavior of these complex systems.

Two new metrics are used to measure and compare the performance of metrology methods. By measuring the revenue generated from a wafer, we can capture the quality of the products produced from that wafer. Therefore, the long run average of the revenue per wafer can be used to measure the quality of the product and the process. Total revenue per day, on the other hand, measures the effects of the combination of yield, throughput and the quality of the products. Manufacturers are usually interested in maximizing their total revenue while minimizing the production cost.

To estimate the expected value of each of these metrics, the results of five days (24 hours/day) are collected in each simulation run. Furthermore, to minimize the effect of randomness, these results are collected based on five different initial random seeds. The results are then presented as a set of graphs that capture the behavior of the system in each scenario. Each point in these graphs is based on the information that is statistically collected from 36000 wafers; each wafer includes 100 dice with individual characteristics. The data are collected after a warm-up period of 50 minutes, which allows the system to go to its stable mode. The "C" code generated by the SIGMA [5] simulation software was modified and used as a platform for generating the data and collecting the information for these experiments.

The lithography throughput is considered to be 60 wafers per hour (one wafer per minute). To accommodate the behavior of a robot in an industrial system, a buffer (with the capacity of one wafer) is considered before and after each station. The performances of these systems are analyzed with respect to changes in *MTBF*, *MTTR*, α, β for each of the inline, insitu and offline cases. Later in this chapter, the effect of control policies, yield/revenue structures, the precision of metrology tools and many other parameters are investigated.

The values of the parameters used in these models are either the estimated values in the industry or what the experts would expect to see in emerging technologies. The experiments are designed to assist the manufacturers with developing similar models. Decision-makers may establish similar experiments which will address their specific needs and will accommodate their parameter values. For the experiments of this section, the center working point of *MTBF* equal to 240 minutes and *MTTR* equal to 20 minutes is chosen. For this working point, five samples are scanned from each wafer and the 3σ rule is used for the cut-off line. It is assumed that the results of the offline metrology are provided half an hour after the main process is done. The information extracted from inline metrology takes less than 15 minutes to be ready, and the results of an insitu metrology will be ready only after a couple of minutes.

Different parameter values will certainly result in different values for our metrics, revenue per wafer and revenue per day. However, readers should keep in mind that the absolute values of these metrics are not in our interest. We are interested in analyzing the changes in metrics values based on the changes in the system. The relative differences will provide us with a better understanding of each system and help us with predicting the behavior of similar systems in similar working conditions.

The assumptions of the previous chapter's model, such as the exponential time between failures and the exponential time to return, are used in the first attempt to develop a simulation system. The results of the simulation model are compared to those of the analytical models from the previous chapter. The second scenario enhances the first scenario by introducing a variance to the process and by considering more realistic structures for the yield and price. In the third scenario, it is shown that in some cases the offline and inline may outperform the insitu technique, even if the quality of information extracted from these systems is assumed to be the same. This scenario shows the importance of the control policy and the market condition in metrology systems.

In the final scenario, more realistic conditions are introduced to the system. Different random errors are considered for each of the inline, offline and insitu tools to capture the different precision associated with each technology. Furthermore, wider and continuous drifts are considered for the process. The results of these scenarios are analyzed and recommendations are made accordingly.

3.1. Analytical Approach vs. Monte Carlo Simulation

A Monte Carlo model is designed to verify the accuracy of the results generated from the analytical models presented in the previous chapter. The assumptions in this model are consistent with the assumptions of exponential failure times and repair times under which the analytical models were developed.

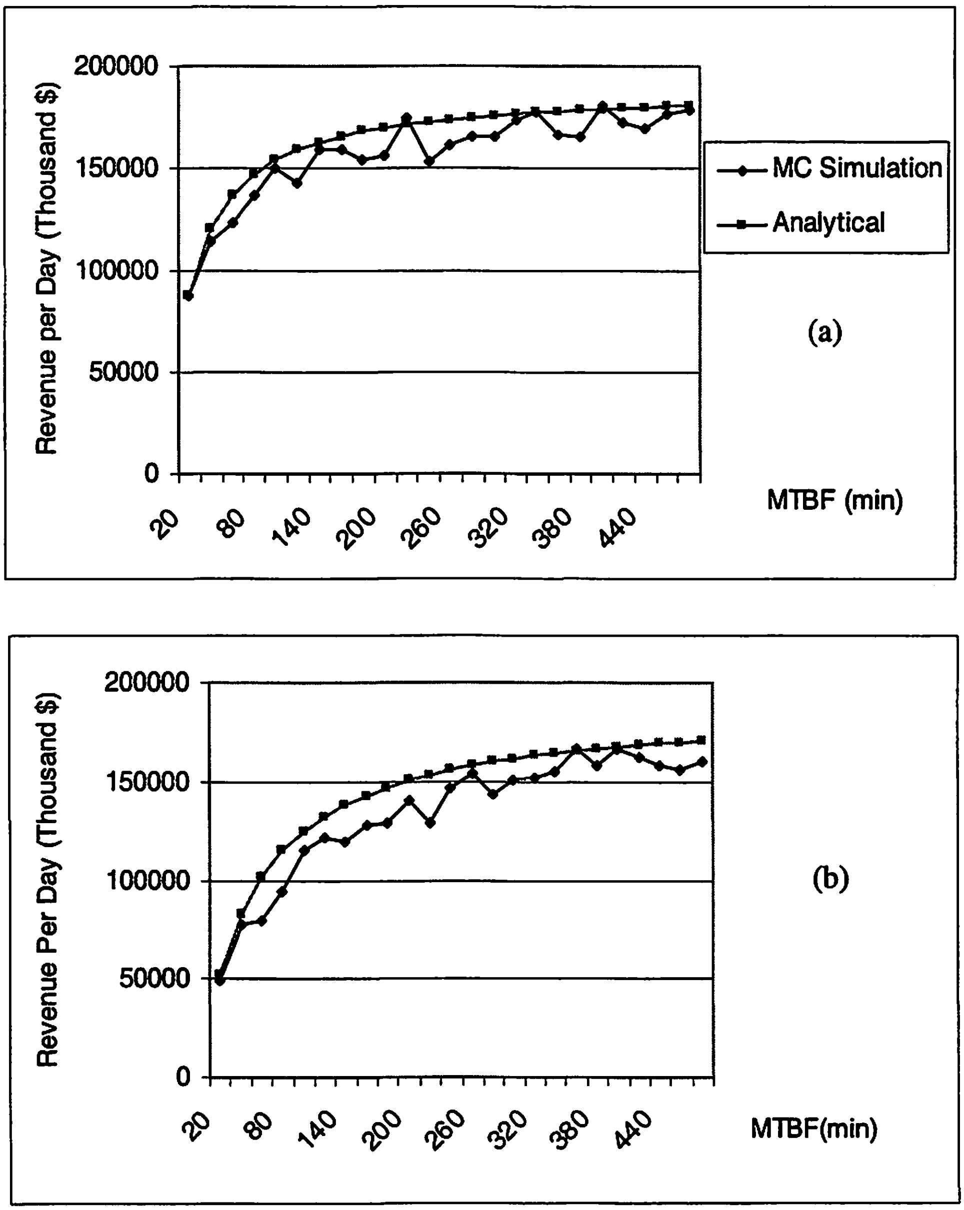

Figure 3.1. Revenue per Day vs. *MTBF* Generated from the Analytical Model and the Simulation for (a) Insitu Metrology, and (b) Offline Metrology

The lithography targets a CD of 205 nm at in-control state. It produces bad products with the CD of 225 at Out-of-Control state. For simplicity, the variance of the process is ignored at this stage; in the next section, the variance will be introduced to the system and its effect will be explored. Good wafers generate $131500/wafer and bad wafers have no revenue values and should be reworked. The CD of 205nm and the revenue of $131500/wafer are chosen to be consistent with the data used in other models in this chapter. These values are discussed and justified in section 3.2.

Figure 3.1 shows the similarity between the generated results from the analytical model (Eq. 5), presented in chapter 2, and the results from the Monte-Carlo simulation. Both the simulation and the analytical model show a big gain in revenue from migrating from offline to insitu, especially in low *MTBF* cases, where the processes go out of control more quickly. Both models show the increase of revenue with increasing *MTBF* values.

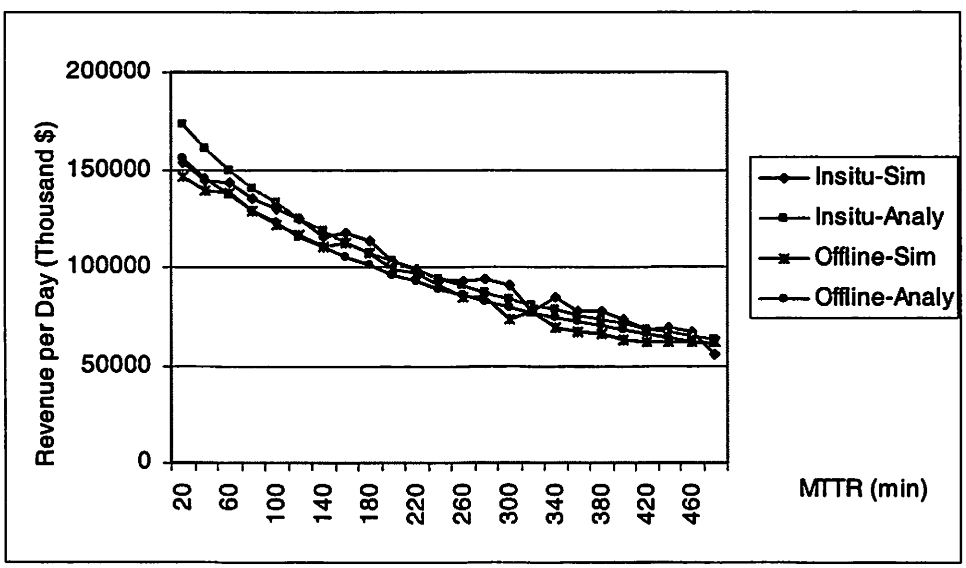

Figure 3.2. Revenue per Day vs. *MTTR* from the Analytical and Simulation models for Insitu and Offline Metrology.

Similarly, Figure 3.2 shows the predicted values for the revenue using Equation 7 in chapter 2 and the simulation results for changes of *MTTR*. Both approaches show a drop in revenue with an increase in *MTTR*. These charts do not show a noticeable difference between insitu and offline metrology, with respect to *MTTR*.

Figure 3.3 shows the effect on revenue of reducing the time between the process and the metrology tool. As expected, it shows an increase in revenue by migrating from offline to inline and insitu technology. Here, only the Revenue per Day charts are shown. The Revenue per Wafer charts in all of the cases in this scenario are flat lines at $131500 because all the bad products are reworked. Introducing the variance to the process will affect the revenue generated for each wafer. The next section will discuss the effects of variance on revenue. The procedure for selecting an appropriate working point for the process also will be reviewed.

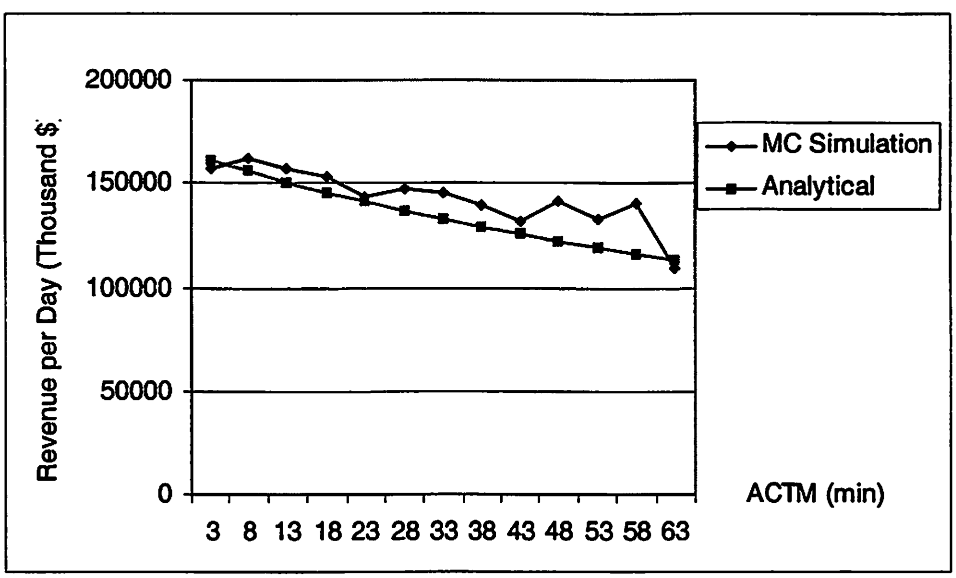

Figure 3.3. Revenue per Day vs. *ACTM* Generated from the Analytical and Simulation Models

3.2. The Effects of Process Variation on Revenue

In semiconductor manufacturing, it is well known that the reduction of the critical dimension results in higher revenue. A study by Motorola* has estimated an average gain of more than $7 per chip for each nanometer reduction of CD.

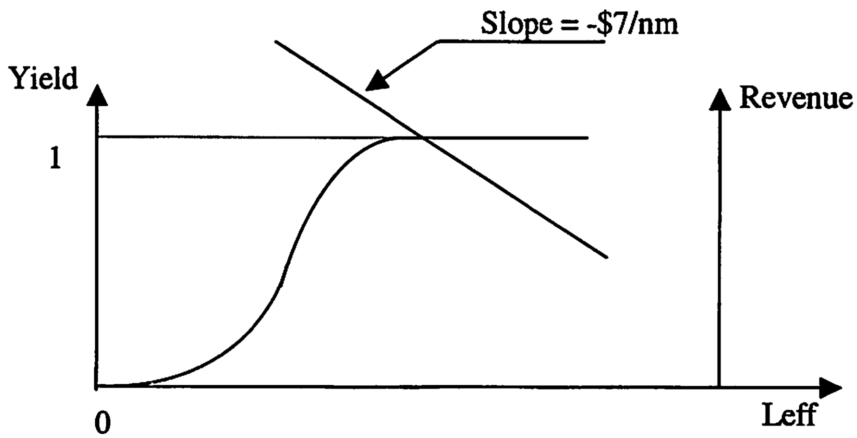

Figure 3.4. Relationship Between Yield, Revenue and CD

However, as shown in Figure 3.4, the reduction of CD may result in downstream manufacturing problems and reduction of yield, which in turn reduces the total revenue. Therefore, targeting the right working point is an essential part of semiconductor businesses. We want to study the effect of variance on the total revenue and find the best working point for each variance. For simplicity, as depicted by Figure 3.5, the yield curve is replaced by a piecewise linear curve, and the revenue curve is replaced by a straight line with the slope of –7$/nm; going all the way to zero. The process distribution is shown as a bell shape with a thick black line. It is assumed that the mean of the process can be adjusted to any value. Therefore, we are interested in finding the best position for the process mean.

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* D.Gerold al, Sematech AEC/APC, Sept 97, Lake Tahoe, NV

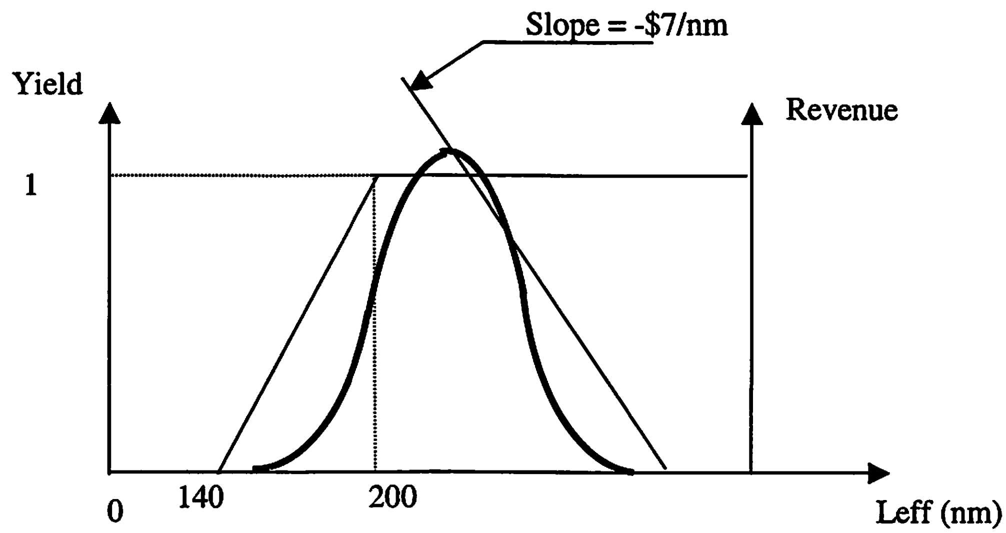


Figure 3.5. A Simplified Picture of Yield and Revenue vs. CD.

Sets of Monte-Carlo simulation models are generated and several experiments are conducted with these models. In these experiments, each wafer carries one hundred chips. The CD of each chip has been generated from a random process following a Normal distribution with a specific mean and variance. The total revenue generated from these chips according to the yield and revenue curves is then calculated. The total revenue is then plotted versus the changes in mean and the standard deviation of the process in Figure 3.6.

The star points in Figure 3.6 show the maximum revenue that can be achieved from the processes with different means but the same standard deviation. Close attention to the behavior of these peaks reveals the reduction of maximum possible revenue with the increase in the standard deviation (Figure 3.7). This indicates that manufacturers should try to minimize the variation in their process to achieve better revenues.

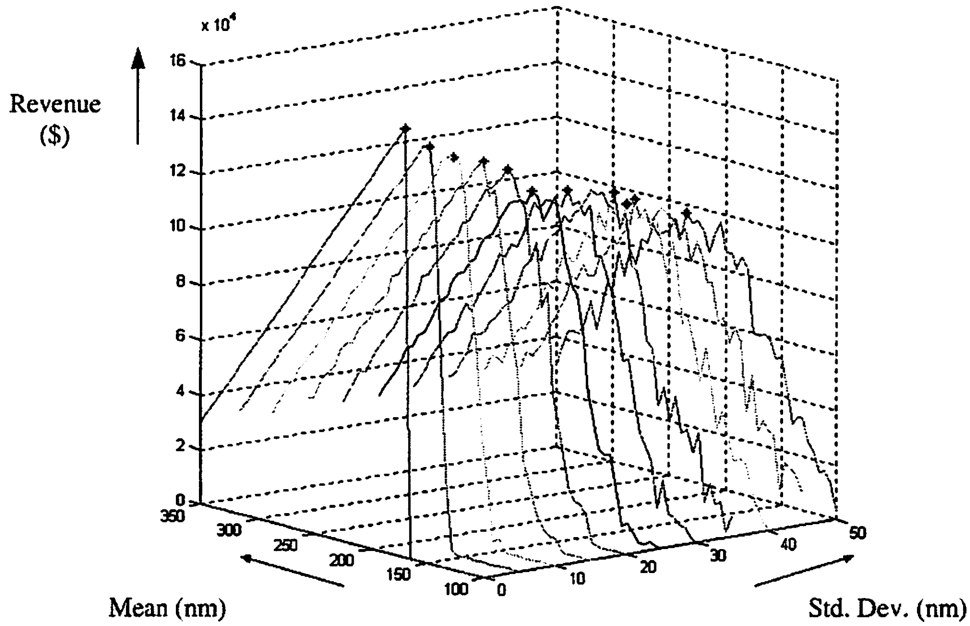


Figure 3.6. Total Revenue Vs. Mean and Standard Deviation of the Process

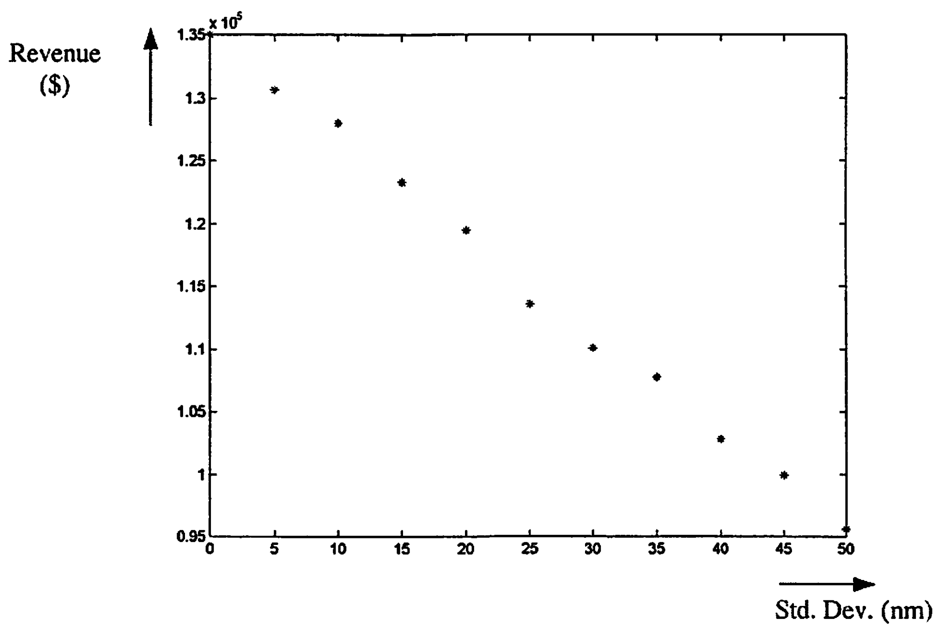


Figure 3.7. Maximum Total Revenue vs. the Standard Deviation of the Process

However, due to practical issues there are always some uncertainties which cause some variation in the process. In these cases, manufactures should choose the best working point for their businesses. For example, if the standard deviation of a process is 10 nm, with the above assumptions, the best working point would be 205 nm.

Figure 3.8 shows this method for finding the best working point based on different standard deviations of a process. For the rest of this document, we assume a standard deviation of 10 nm associated with the process, and we try to keep the working point at 205 nm in order to gain the maximum revenue. Assuming a revenue of \$1000 per chip for a CD of 250 nm will result in a revenue of \$1315 per chip for a CD of 205 (with the –7\$/nm decline rate). The revenue of \$131500 per wafer (each wafer includes 100 chips) is used for the quality wafers with the CD of 205 nm throughout this chapter.

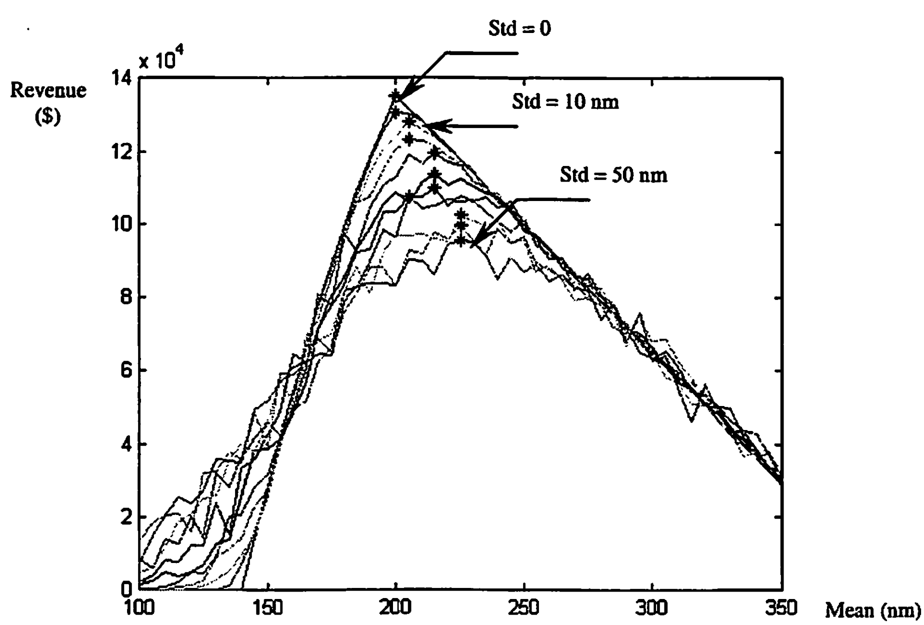


Figure 3.8. Revenue vs. Mean of the Process for Different Standard Deviation

Another negative effect of variance on revenue is due to the risk involved in measuring the products. As described in Chapter 2, α and β, are the risks of rejecting the process while the process is in control, and accepting the process when the process is out of control, respectively. The process variance has a direct affect on these risks.

To investigate more complex systems, a process variance of 10 nm is introduced to the simulation model which was developed earlier in this chapter. The process is targeted to work at 205 nm but it may go to the bad state of 225 nm after a random time period with the distribution of *N(MTBF, MTBF/10)**. The process stays in the bad state until detected by the metrology tool. The shutdown/repair signal is generated when the average of the CDs measured from the sample points exceeds the cutoff line threshold. The process is then shut down and all the bad products in WIP are sent to rework. The process will be back in good state after a random repair time with the distribution *N(MTTR, MTTR/10)*. The $7/nm rule is observed in this case and there is no revenue for the products with more than 220 nm CDs, reflecting tight specifications set by management. Figure 3.9 shows the in-control case in comparison to the out-of-control case.

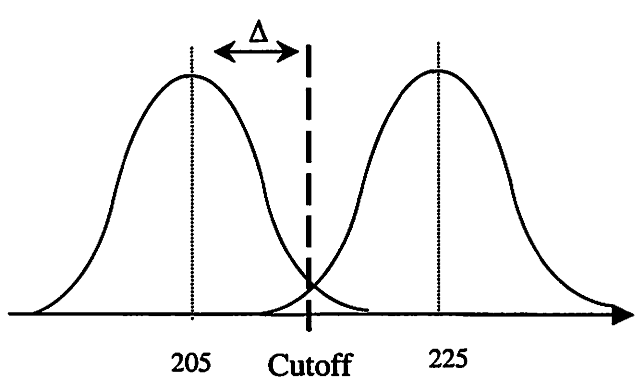


Figure 3.9. In-Control vs. Out-Of-Control

* $N(\mu, \sigma)$ represents a normal distribution with mean μ and standard deviation of σ.

To measure the performance of the system versus the measurement risks, we need to control the values of α and β. However, it is difficult to directly manipulate the values of these parameters. We achieve these goals by changing the number of sample points taken from each wafer and by adjusting the cutoff line of control policy. Suppose Z_ζ represents the point on the Standard Normal distribution *N(0,1)* with the probability of upper tail equal to ζ. Then the following equations hold

$$\frac{X-205}{10/\sqrt{n}} = \frac{\Delta}{10/\sqrt{n}} = Z_{(1-\alpha)}$$

$$\frac{X-225}{10/\sqrt{n}} = \frac{20-\Delta}{10/\sqrt{n}} = Z_{\beta} \qquad \text{(Eq. 24)}$$

Where n is the number of sample points in each wafer and Δ is the cutoff point as shown in Figure 3.9. The number of sample points can be calculated as

$$n = \frac{(Z_{(1-\alpha)} - Z_{\beta})^2}{4} \qquad \text{(Eq. 25)}$$

To obtain the desired α and β, first the number of sample points (n) is calculated. This value is then rounded to the closest integer. Then, the value of Δ is obtained. Δ and n, together, will specify new values for α and β, which are very close to the desired values. For example, the standard 5 sample points along with the 3σ (Δ =13.41nm) rule for cutoff results in values of 0.0013 and 0.0702 for α and β, respectively. Whenever possible, these values are set for the working point of the model. Figure 3.10 - Figure 3.14 show the performance of this system with respect to the changes in the parameters of the system.

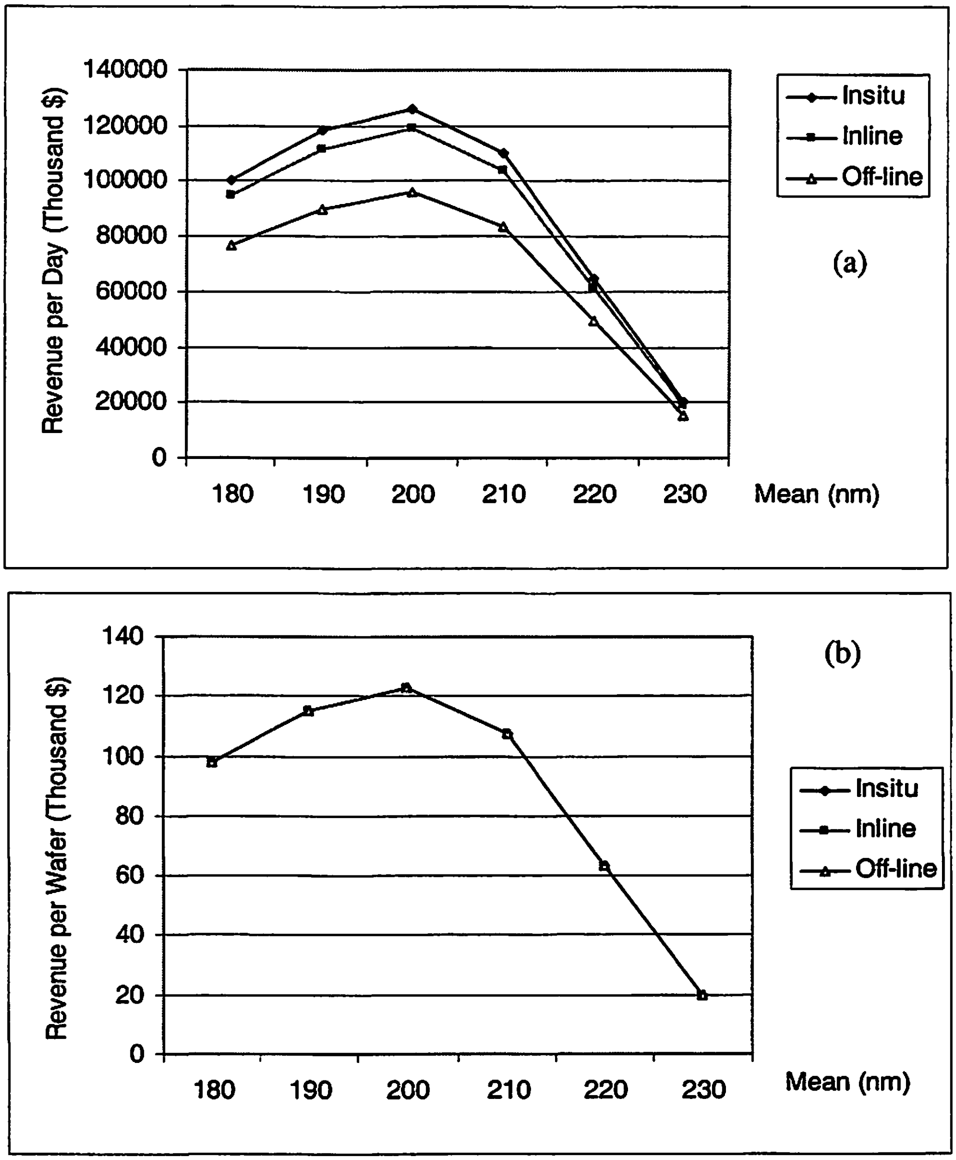


Figure 3.10. Revenue Generated vs. Different Values of the Process Mean (a) Revenue per Day, and (b) Revenue per Wafer.

Similar to Figure 3.8, Figure 3.10 shows a big drop in the total revenue and the quality for out of control processes and depicts the importance of choosing the correct working point. Furthermore, it shows that the insitu model, regardless of the mean value, outperforms the inline model, which in turn outperforms the offline techniques. However, this figure doesn't show any noticeable difference between the qualities of products produced with each technique.

Figure 3.11 shows the importance of *MTBF* in generating revenue. It should be noted that changes in *MTBF*, especially at low values, have a bigger impact on revenue than changes of equal magnitude when *MTBF* has high values. Furthermore, the insitu method here again shows better revenue than the inline and offline techniques.

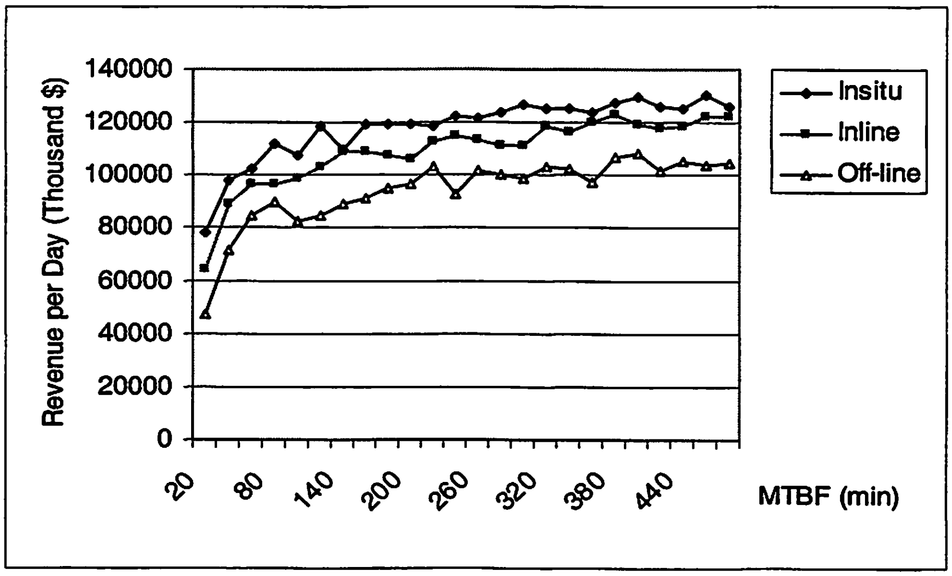


Figure 3.11. Revenue Generated vs. Different Values of the *MTBF*.

The revenue-per-wafer charts in this experiment are mostly flat lines and do not reflect noticeable disparities with the changes of *MTBF*, *MTTR* and α. Therefore, they are not shown in this section.

The change in the revenue of this system versus the changes in *MTTR* is depicted in Figure 3.12. As expected, it shows a decrease in revenue with the increase in *MTTR*. Furthermore, the rate of change of the revenue decreases with the increase of *MTTR*. Similar to previous charts, the insitu method here outperforms the inline and offline methods.

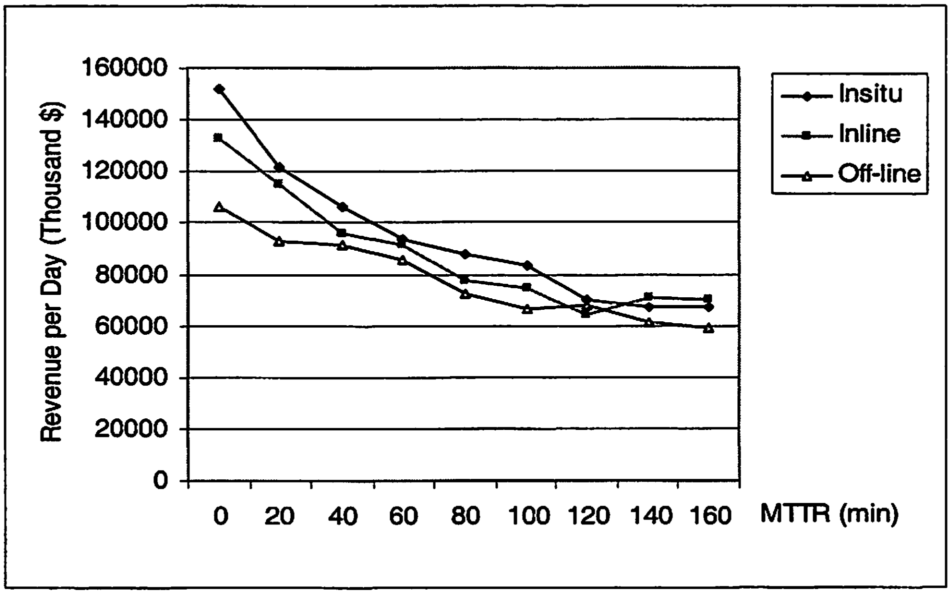


Figure 3.12. Revenue Generated vs. Different Values of *MTTR*.

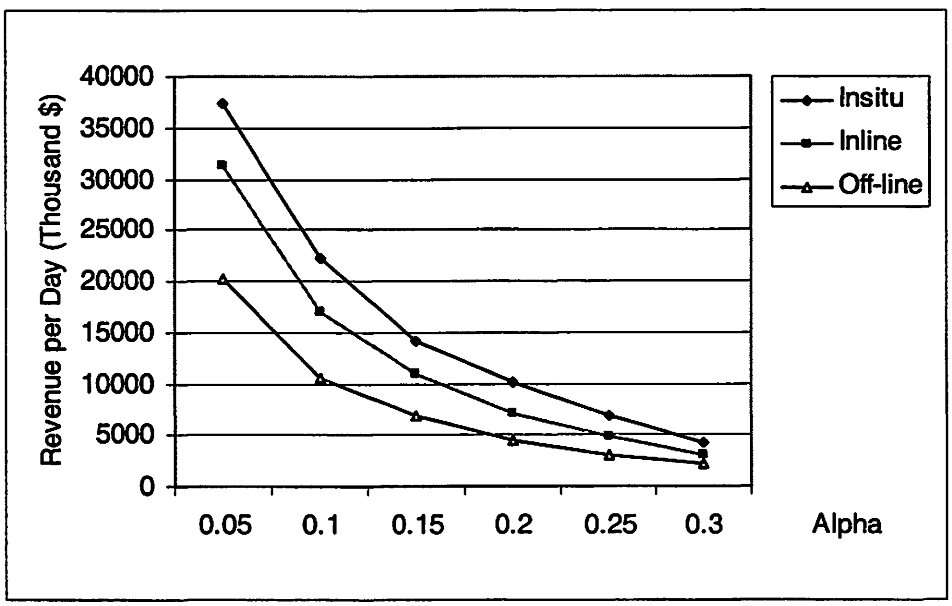


Figure 3.13. Changes of Revenue vs. Changes in Type I Error.

Figure 3.13 captures the effect of type I error (α) on the revenue. As α increases, more repair/shutdown signals are generated by the metrology tool which results in frequent shutdowns of the system and therefore, production loss. On the other hand, the model shows that the quality of products is not sensitive to changes in α.

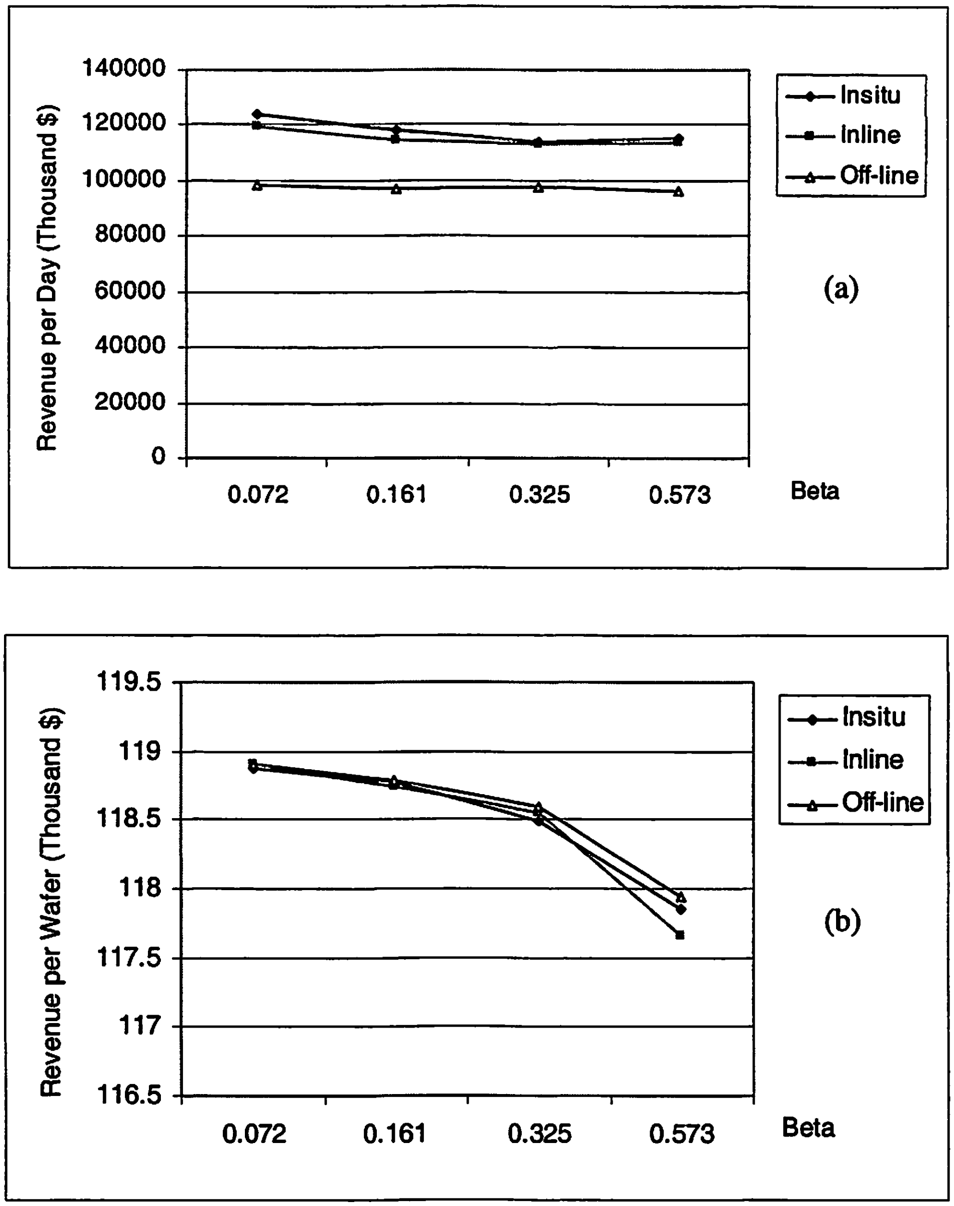


Figure 3.14. Changes of Revenue vs. Changes in Type II Error. (a) Revenue per Day, and (b) Revenue per Wafer.

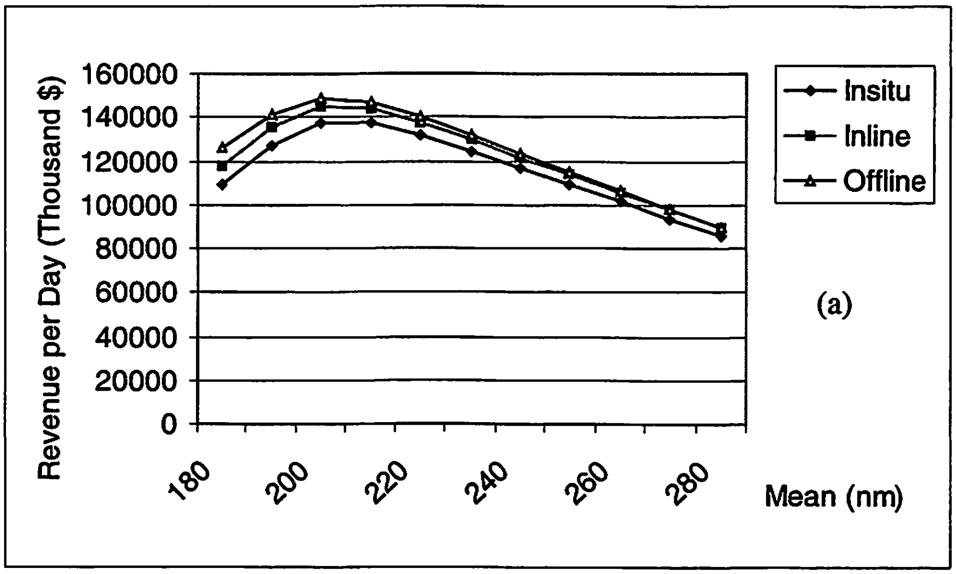
Type II error (β), on the other hand, has a noticeable effect on the quality of the products. By increasing β, more bad products are produced while the process is considered to be in control. In this case, total revenue per day is not that sensitive to the changes of β and shows only slight decline with the increase of β.

In all of the cases studied up to now, insitu metrology outperformed inline and offline setups. Now, the question arises whether the insitu method is always a superior method; if not, what are the factors that may affect its performance?

3.3. A Case Where Offline Method Outperforms Insitu Method

Analytical models presented in Chapter 2 predict some of the situations where the offline methods may outperform the inline and insitu methods. Most of these situations are due to the better characteristics and the quality of information extracted from the offline methods. In this section, we study the case where the offline metrology outperforms the insitu, with the exact same specifications.

Consider the scenario discussed in section 3.2, where the process is targeted to work at 205 nm but it may go to the bad state of 225 nm after a random time with the distribution of *N(MTBF, MTBF/10)*. The process is then shut down and repaired and will be back in good (in control) state after a random repair time with distribution *N(MTTR, MTTR/10)*. But, here we assume that the bad WIP is sent for further processing and marketing without being reworked. Furthermore, in this scenario, the feature specifications are not as tight as the previous scenario. The revenue declines at the rate of –7\$/nm up to 380 nm, after which there is no revenue. Figure 3.15 - Figure 3.17 show the revenues generated in this scenario.



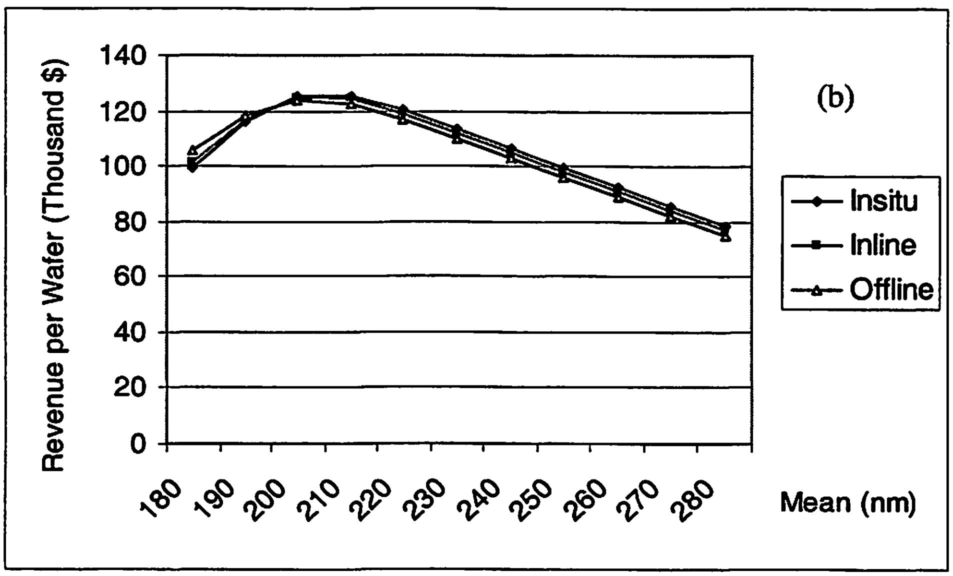


Figure 3.15. Revenue Generated vs. Different Values of the Process Mean (a) Revenue per Day, and (b) Revenue per Wafer.

Figure 3.15 shows that the offline metrology slightly outperforms the inline and insitu metrologies regardless of the targeted process mean. The quality of products, on the other hand, doesn't show noticeable differences between offline and insitu setups. Further study of revenue per wafer charts reveals that in this scenario the production of bad wafers is not sufficiently penalized. Let us consider the behavior of the system with respect to the changes in the type I error (α). Figure 3.16 shows that increasing α will slightly increase the value of the wafers because of the production of good quality wafers.

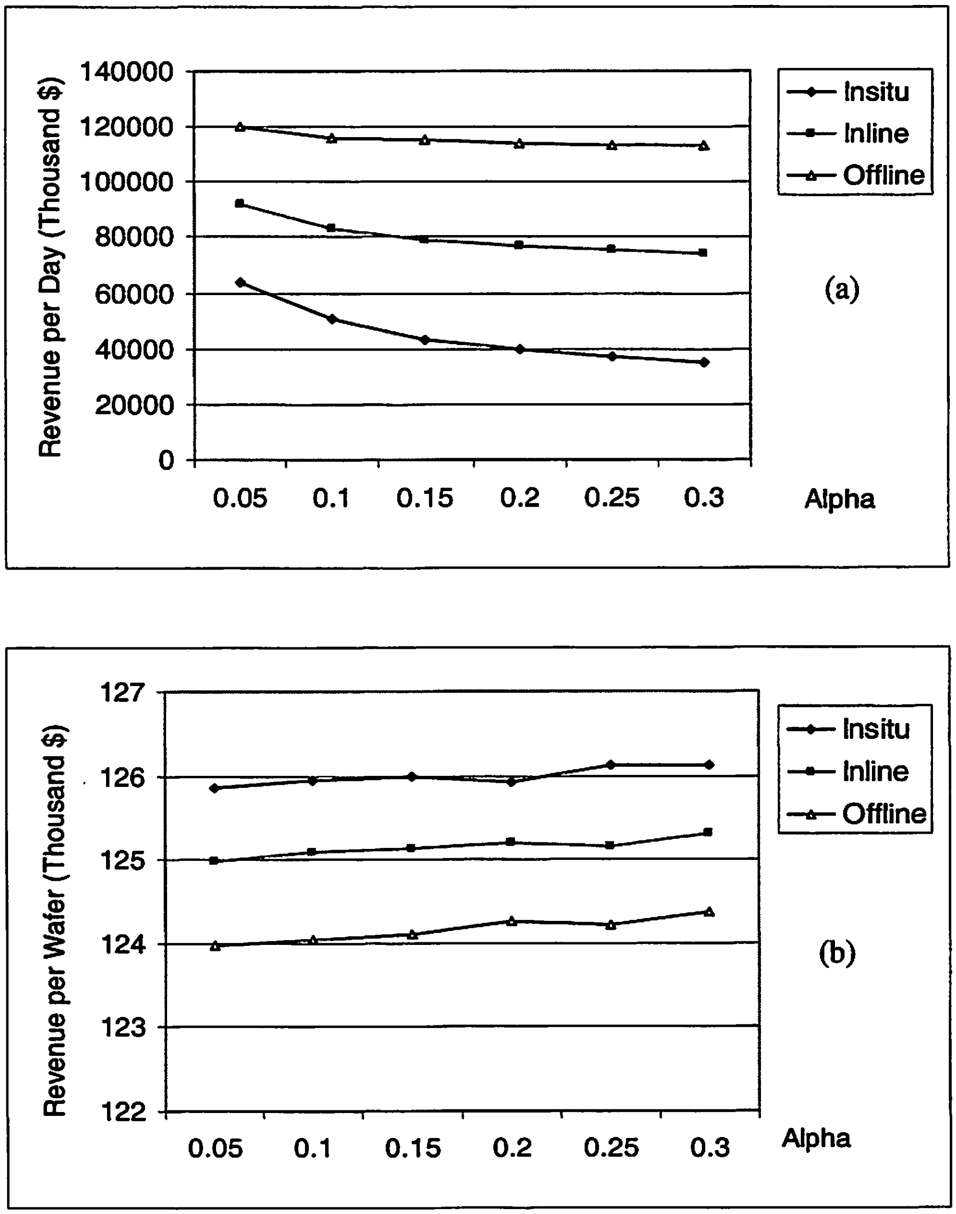


Figure 3.16. Revenue Generated vs. Different Values of the Type I Error
(a) Revenue per Day, and (b) Revenue per Wafer

On the other hand, increasing α, corresponds to an increase in the number of false alarms in the system, which in turn reduces the throughput and drops the total revenue. Figure 3.16 (b) shows a slight decrease of revenue by increasing α. Comparing these results with Figure 3.13, where the drop in the revenue is much steeper, reveals that in this scenario, producing bad products does not severely affect the total revenue.

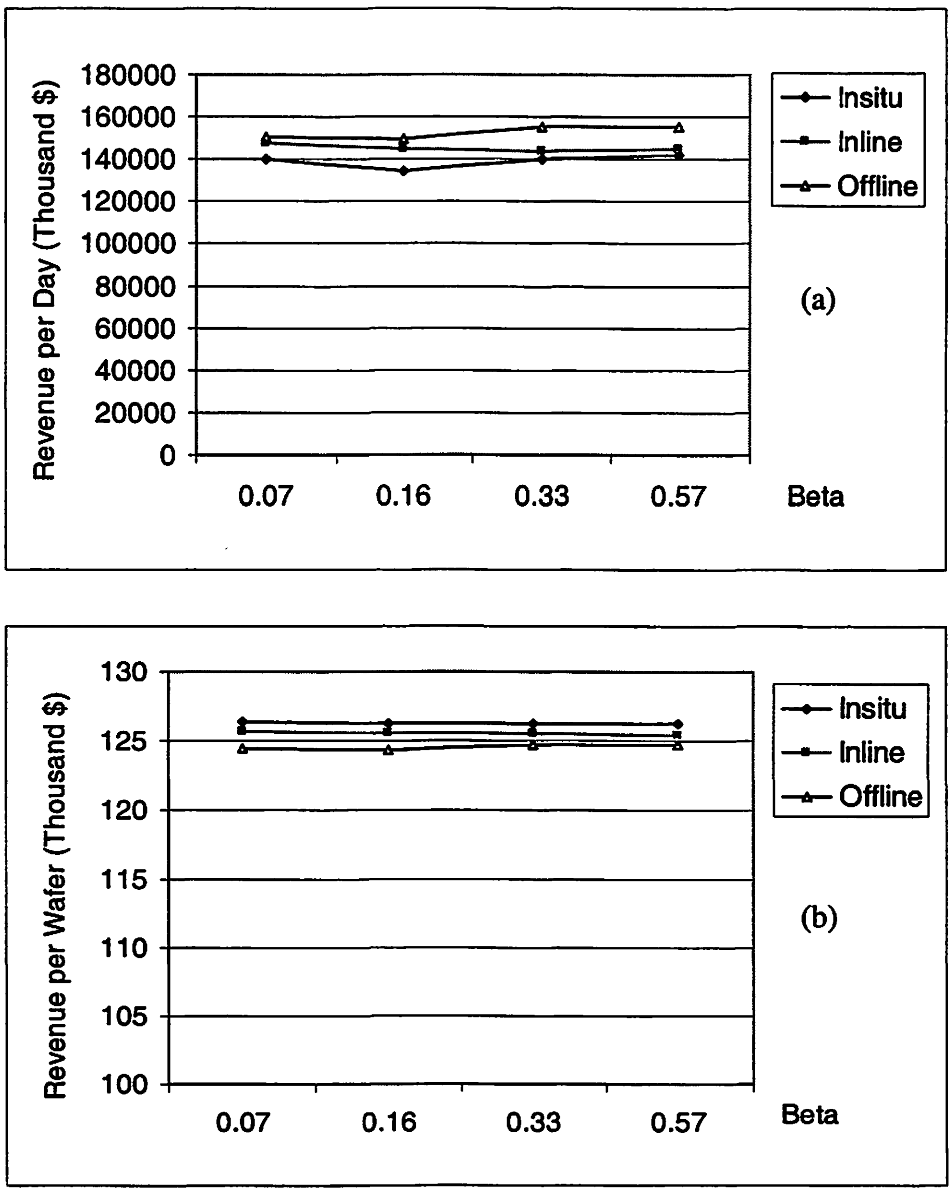
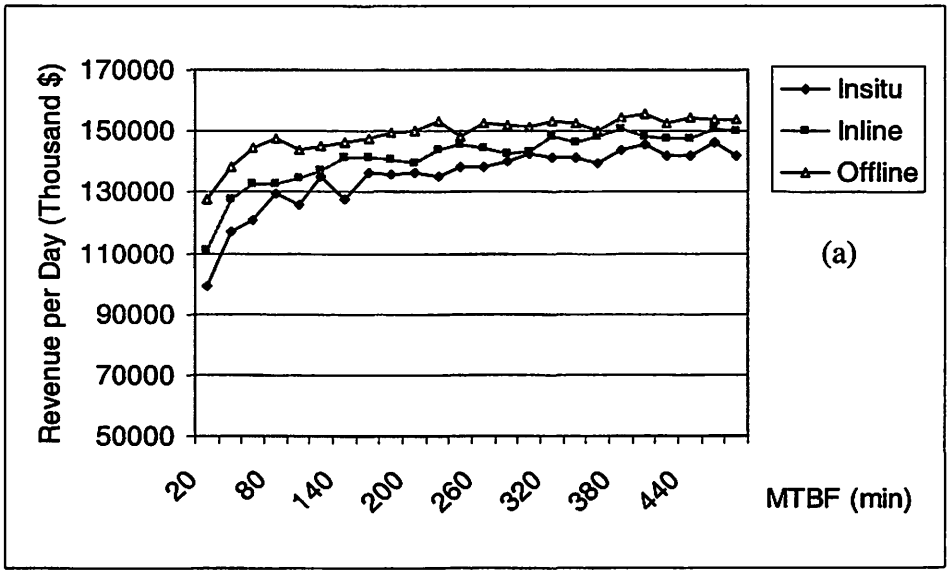


Figure 3.17. Revenue Generated Based on Different Values of Type II Error
(a) Revenue per Day, and (b) Revenue per Wafer



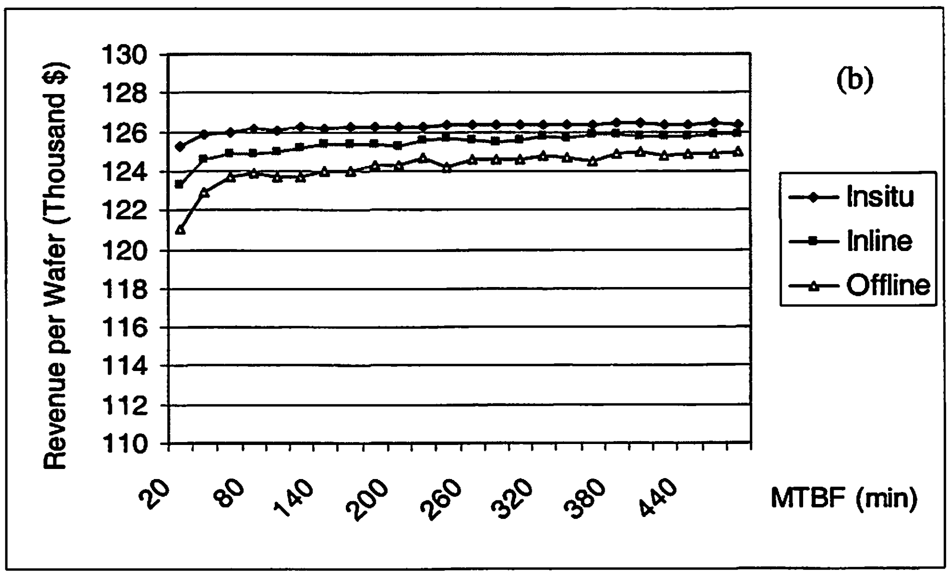


Figure 3.18. Revenue Generated vs. Different Values of the *MTBF*
(a) Revenue per Day, and (b) Revenue per Wafer

Changing the Type II error (β) does not have a noticeable effect on the revenues generated by each wafer and the total revenue generated in this scenario (Figure 3.17). This is due to the fact that when the process is in the out-of-control state, it continues producing products that are still marketable and there are customers that are willing to pay a high price (slightly less than the premium) for these products. In this situation, manufacturers may have the incentive to postpone the repair of the bad system, because almost all of the products, regardless of their qualities, are marketable.

All of the charts associated with this scenario show that insitu outperforms the inline and offline methods in terms of the quality of produced wafers. However, the quality by itself does not justify the method. The lost revenue due to the production lost in insitu offsets the increased revenue due to better products. Therefore, here, the total revenue in an insitu setup is less that the total revenue of inline and offline setups. The revenue vs. *MTBF* and *MTTR* charts - Figure 3.18 and Figure 3.19- are also consistent with this conclusion. This scenario shows the importance of choosing an appropriate control policy based on the system parameters and the price structures.

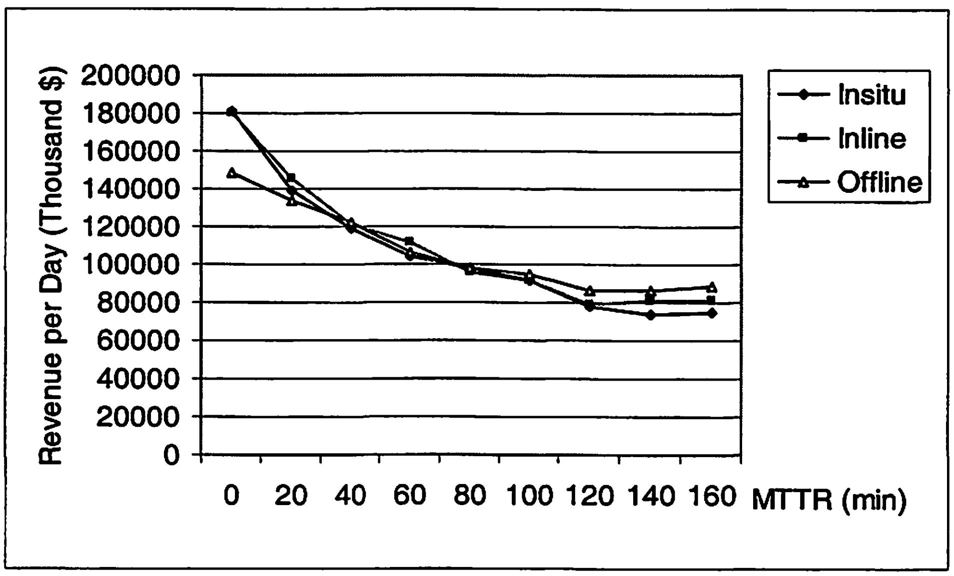


Figure 3.19. Revenue Generated vs. Different Values of *MTTR*

3.4. Modeling A Complex System

In trying to model more complex systems, a scenario is designed that enhances the previous models presented in this document. Previous models considered the precision of metrology tools embedded in α and β. Here, we introduce the precision of metrology tools as a parameter in the system and study its effect on system's performance. Furthermore, in this case, the changes in the targeted mean may occur gradually. In other words, there are infinite numbers of out-of-control states in the system. New market observation shows steeper line for the revenue based on the changes in CD. The price decline rate has also been modified to accommodate the recent changes in the market.

In this scenario, the process is targeted to work at 205 nm but it may drift after a random time with the distribution of *N(MTBF, MTBF/10)*. The new working point can be anywhere in the [0, +30] nm neighborhood of the previous working point. The process keeps changing the working points (getting worse and worse) until it gets detected by the metrology tool. The metrology tool gathers the data from several points on each wafer according to its precision.

Here, we introduce noise to each measured point with a distribution of *N(0, Std_ERR)*. This noise models the precision of the metrology tool. The standard deviation of these noises for the central working point are set to the values of 3nm, 2nm, and 0.5nm respectively for insitu, inline and offline metrology tools.

The shutdown/repair signal is generated when the average of the CDs measured from the sample points exceeds the cutoff line threshold. The process is then shut down and all of the bad products in WIP are sent to rework. The process will be back under control after a random repair time with the distribution of *N(MTTR, MTTR/10)*. Our observation of the current advanced logic market shows an approximate of $10/nm drop for the price of each chip. The $10/nm price drop is implemented in this case and there is no revenue for the products with more than 220 nm CDs. Figure 3.20 - Figure 3.23 show the system performance versus the changes in the system's parameters.

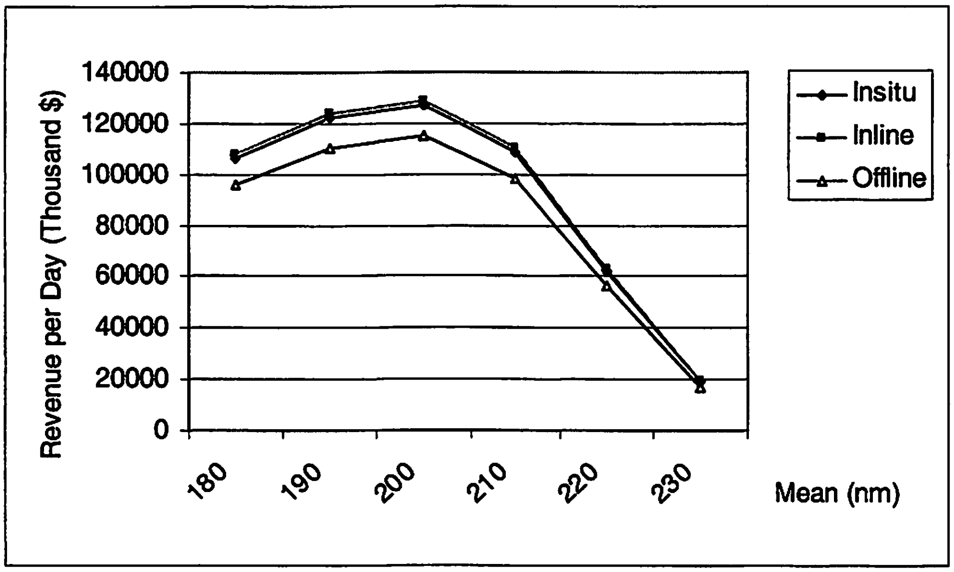


Figure 3.20. Total Revenue Per Day vs. the Process Mean For the Complex System

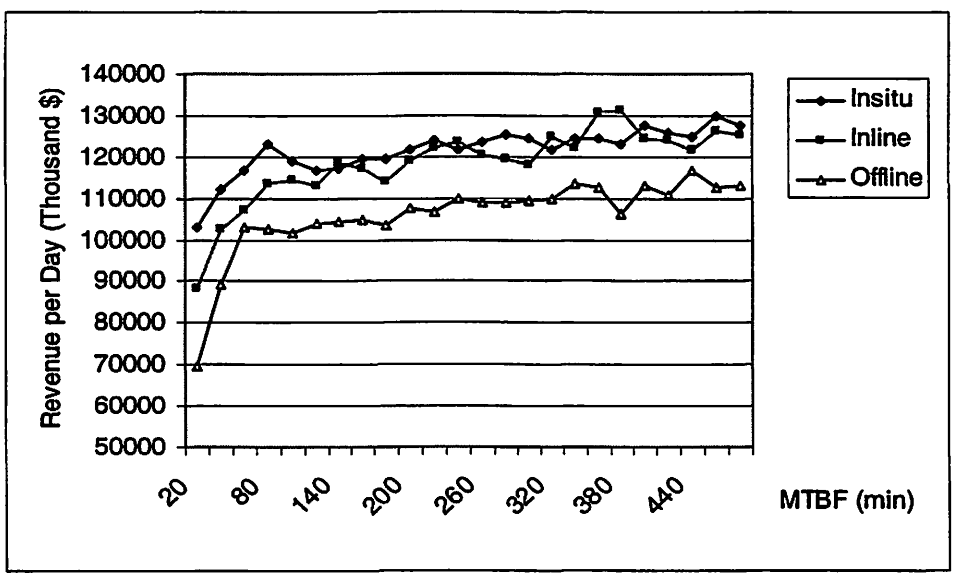


Figure 3.21. Total Revenue Per Day vs. MBTF for the Complex System

Revenue per wafer charts do not show noticeable changes with the change of these parameters. Therefore, they are not included in this document.The first three charts are similar to those of previous cases. All of these charts show that the insitu methods are slightly superior to the inline and offline methods.

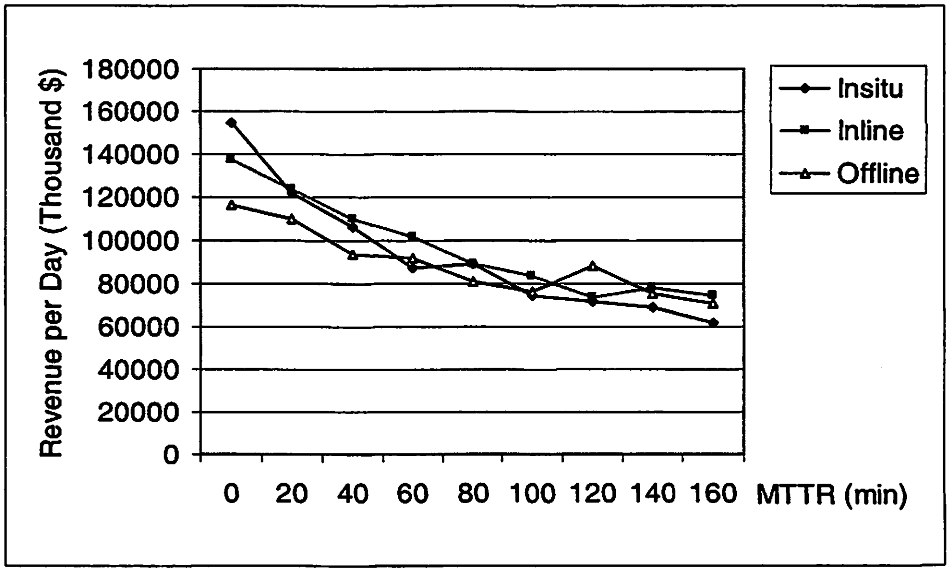


Figure 3.22. Total Revenue Per Day vs. *MTTR* for the Complex System

Figure 3.23, shows the effect of the metrology precision on the total generated revenue. The chart depicts that the revenue is very sensitive to the changes of precision. This chart can be used to justify the migration from offline to inline and insitu based on the precisions achieved by the different technologies. It can further be used to identify the break-even points of each of these technologies. For example, according to Figure 3.23, migrating from offline to insitu is justified when the offline and insitu respectively have precisions of 0.5 nm and 3nm, but it cannot be justified if the insitu precision is greater than 6nm.

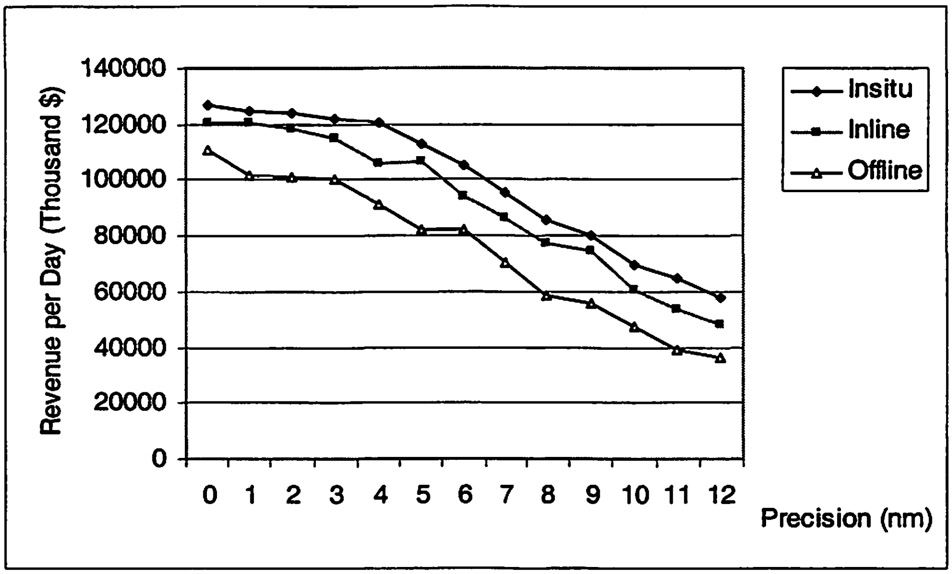


Figure 3.23. Total Revenue Per Day vs. Metrology Precision for the Complex System

4. Summary and Conclusions

This document provides a framework for the economic analysis of metrology tools in semiconductor manufacturing. Several qualitative and quantitative models were presented in this document in order to study the elements of revenue and cost in semiconductor manufacturing due to different metrology tools and practices. The differences between insitu, inline and offline metrology systems were emphasized. The proposed models should be modified and adjusted to address the practical issues in an industrial environment.

A framework was suggested for the steady state case based on a continuous time Markov Chain model. Based on this framework, two analytical models were developed. The first model emphasizes the revenue generated from each system. This model mostly reflects marketing value. The revenue model was extended to include the revenue loss due to the delayed time-to-yield in ramp up phases. On the other hand, the second model focuses on system costs. The cost model estimates the expenses of the manufacturing system to satisfy certain demands for a long period of time. These analytical models present the important factors that affect the performance of the system and depict the relationship among these factors.

To study more complex systems, Monte Carlo simulation models were generated. These models were used to study each system under different scenarios. Two metrics, "revenue per wafer" and "revenue per day" were introduced to measure the quality of the wafers and the total revenue. Total revenue, in turn, captures the effect of many factors such as the quality of products, the production rate and the market behavior. Different price and yield structures were implemented in these scenarios. Many complexities were introduced to these systems, the results were analyzed, and appropriate recommendations were made.

All of these models confirmed the importance of selecting appropriate metrology tools and methods. The revenue and the cost of these systems are very sensitive to metrology tool specifications, metrology structure and even the control policies. In most situations, especially when the process is newly introduced and the failure rate is high, the insitu metrology outperforms the inline and offline methods.

To make the decision to migrate from offline to inline and insitu, many factors should be taken into account. The expenses of purchasing, installing and long-term maintenance costs along with the footprint, labor and material costs should be considered. The quality of products and the revenue associated with each technique should be studied. Both the market situation and the control policy play important roles in the decision-making process. Insitu and inline metrology provide better response times than offline metrology, and are very useful especially in ramp-up phases. However, the quality of information extracted from these methods should be comparable with the offline methods. Future technologies will reduce this gap and it is expected that insitu metrology will become the main trend in semiconductor industry.

There are not that many publications about the economic aspects of metrology tools in semiconductor manufacturing. More studies should be conducted to capture the effect of different factors on metrology tools in different environments. The analytical models presented in this document should be further enhanced to address more practical issues. The accuracy and the sensitivity of these models should be assessed in industrial environments and adjustments should be made accordingly. Hybrid methods, with the combination of inline, insitu and offline should be studied. One approach may be to emphasize inline information with tight specifications during the introduction of a process and gradually change the emphasis to offline as the process matures. In general, effective and efficient algorithms should be developed for data acquisition and control of metrology systems.

5. Appendix A. Notations

α = Type I error; the probability of rejecting a process (or product) while the process is in control.

β = Type II error; the probability of accepting the process (or product) while the process is out of control.

γ = Continuous discount factor calibrating the declining price, whereby the revenue per wafer on day t is given by $R(t) = R_0 e^{-\gamma t}$.

ACTM = Average Cycle Time to Metrology; is the expected elapsed time of a product from the main process to the metrology tool (expressed in hours).

Ce_i = Amortized purchase and installation cost plus annual maintenance cost per machine of equipment type i (expressed in dollars per year).

D = Designed die output capacity at mature yield (expressed in units per month).

D_R = Designed die output capacity at the Ramp-up phase (expressed in units per month)

Le_i = The portion of labor cost (wages, salaries, benefits) that is proportional to the number of machines of equipment type i (expressed in dollars per year).

Lf = fixed labor cost, i.e. the portion of labor cost that is independent of wafer start volume and the installed equipment (expressed in dollars per year).

Lw = The portion of labor cost that is proportional to the number of wafers started, per wafer start (expressed in dollars per year).

Lw_r = The portion of labor cost that is proportional to the number of wafers reworked at machines of equipment type i, per wafer reworked (expressed in dollars per year).

$MTBF$ = Mean Time Between Failure; is the average time between two consequent failures of a process(expressed in hours) .

$MTTR$ = Mean Time To Return; is the expected repair time when the process has failed (expressed in hours).

Mw = Material cost, assumed to be proportional to the number of wafers started, per wafer start (expressed in dollars per year) .

Mw_r = Material cost (such as mask expenses, coating and developing consumables,...) assumed to be proportional to the number of wafers reworked at machines of equipment type i, per wafer reworked(expressed in dollars per year).

N_i = Number of machines of type i that are installed in the factory.

OEE_i = Overall equipment efficiency of equipment type i, before considering the losses due to characteristics under study and the metrology tool control policy; assumed to be constant over the factory operating life.

OEE_i^*= Overall equipment efficiency of equipment type i, after considering all the losses (including losses due to metrology tool control policy); assumed to be constant over the factory operating life.

P_0 = Long term probability that the process will be in In-Control state in the mature phase.

P_{0R} = Long term probability that the process will be in In-Control state in development and ramp up phase.

P_1 = Long term probability that the process will be in Out-of-Control state in the mature phase.

P_{IR} = Long term probability that the process will be in Out-of-Control state in development and ramp-up phase.

R_0 = Sales revenue on the first day per 100%-yielding wafer (expressed in dollars)

Se_i = Occupancy cost plus amortized capital cost for factory facilities and infrastructure per machine of equipment type i (expressed in dollars per year). This is the portion of total facility and infrastructure cost that is proportional to the floor space allocated per machine of equipment type i.

Sw = The portion of total facility and infrastructure cost that is proportional to the number of wafers started, per wafer started (expressed in dollars per year).

Sw_r = The portion of total facility, energy and infrastructure cost that is proportional to the number of wafers reworked at machines of equipment type i, per wafer reworked (expressed in dollars per year).

Sf = Fixed space cost, i.e. the portion of total facility and infrastructure cost that is independent of wafer volume and installed equipment (expressed in dollars per year) .

$ThPT_i$ = Total theoretical process time per wafer (expressed in hours) on equipment type i, considering all process steps performed by that equipment.

Y_F = Mature die yield. The fab produces $W= D/Y_F$ per month in each month of operation. (A month is defined as one-twelfth of a year that includes 360 working days, each with 24 working hours.)

6. References

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