A Strategy and Decision Model for Reducing the Total Cost of Semiconductor Manufacturing Equipment

by

Melinda Keyser

B.S., Electrical Engineering
Clarkson University, 1988

Submitted to the Sloan School of Management and
the Department of Electrical Engineering and Computer Science
in Partial Fulfillment of the Requirements for the Degrees of

Master of Science in Management
and
Master of Science

at the
Massachusetts Institute of Technology
June 1995

Signature of Author..............................
MIT Sloan School of Management
Department of Electrical Engineering
May 12, 1995

Certified by...
Dr. Lionel C. Kimerling, Professor
Department of Materials Science and Engineering
Thesis Advisor

Certified by...
Dr. Charles H. Fine, Associate Professor
Sloan School of Management
Thesis Advisor

Accepted by..
Jeffrey A. Barks, Associate Dean
Sloan Master's and Bachelor's Programs

Accepted by...
Frederic R. Morgenthaler, Chairman
Committee on Graduate Students

A Strategy and Decision Model for Reducing the Total Cost of Semiconductor Manufacturing Equipment

by

Melinda Keyser

Submitted to the Sloan School of Management and
the Department of Electrical Engineering and Computer Science
in Partial Fulfillment of the Requirements for the Degrees of

Master of Science in Management
and
Master of Science

ABSTRACT

Intel Corporation, like many semiconductor manufacturing firms, has shifted its equipment procurement focus from initial cost to total cost of ownership over equipment lifetime. As a result, an increased emphasis on equipment maintenance and support has been driven back through the value chain, from the factory floor through the capital purchasing department to the supplier base. Equipment sourcing decisions are justified by total cost analysis, and suppliers who offer total cost reduction solutions are in a favorable position for contract negotiation. These forces, as well as internal emphasis on total cost reduction, has driven teams within Intel and its supplier base to pursue performance improvement projects which will ulitmately improve total cost.

This thesis presents a generic methodology for identifying cost reduction opportunities, generating root cause solutions, and prioritizing improvement effort. The thesis also introduces the *Equipment Change Impact Model*, a Microsoft Excel application designed to help teams:

- compare improvement strategies to determine the most cost effective alternative
- determine the potential savings, NPV and payback period of a proposed equipment change
- analyze the effect of data variability on decision strategies

This model is based on the SEMATECH total cost of ownership model, but has the added benefit of determining projected, best and worst case financial returns of a proposed change. A qualitative matrix section enhances the financial model by taking into account non-quantifiable data. Applications and case studies using this approach are presented.

Thesis Advisors

Dr. Charles H. Fine, Associate Professor, Sloan School of Management
Dr. Lionel C. Kimerling, Professor, Material Science Engineering Department

Acknowledgements

This thesis is the result of extensive research at Intel Corporation in Phoenix, Arizona in conjunction with the Leaders for Manufacturing Program at MIT. I would like to gratefully acknowledge the Leaders for Manufacturing Program for its support of this work, as well as David Marsing at Intel, who has actively supported the program in an operating committee role.

I am very grateful to Randy Bollig, Logan Sage, and Bob Bruck from the Intel Corporate Capital Acquisition department for sponsoring this project. Each served as an excellent mentor throughout the internship and provided many opportunities for me to gather data and present my results throughout the corporation.

There are others at Intel who willingly shared ideas and data with me throughout my intership. Moses Mares, Gulsher Grewal, Peter Silverman, Caroline Seward, Vickie Ideta, Jenny Wheeler, John Lyman, Dave Troness, and John O'Hara are just a few of many supporters who contributed to this project.

I would also like to thank my thesis advisors, Professors Charles Fine and Lionel Kimerling, who provided resources and constructive criticism throughout my internship.

Finally, I would like to dedicate this thesis to my parents, Joan and Bill Keyser, and my brother Mark for their love and support, even when my career carries me far from home.

Bibliographical Note

Melinda Keyser graduated from Clarkson University in Potsdam, NY in 1998 with a Bachelor of Science in Electrical Engineering. Upon graduation she worked in the Aerospace and Transportation Divisions of the General Electric Company as part of the Manufacturing Management Program. After completion of the program she held positions in supplier quality engineering and program management at GE Transportation Systems in Erie, PA. Melinda joined the Leaders for Manufacturing Program at MIT in 1993, and completed her research internship at Intel Corporation in Phoenix, Arizona. After graduation she plans to return to Intel as an Industrial Engineering Group Leader in their new wafer fabrication facility.

Table Of Contents

CHAPTER 7

CHAPTER 8

Chapter 1

Introduction

In the past decade the semiconductor industry has experience a profound change in manufacturing complexity as consumers, software partners, and chip designers demand faster processing speeds within smaller packages. In contrast to some industries where product design alone determines strategic success, semiconductor design paradigms are dictated by existing manufacturing equipment capability. As a result, the role of the capital purchasing organization of Intel, and other semiconductor manufacturers, has changed from a simple procurement function to a vital link in determining future technology leadership via strategic alliances with equipment manufacturers.

To meet this challenge, capital acquisition decisions are based on the total cost of equipment over its lifetime, rather than historical methods based on initial cost of equipment and installation costs alone. Total cost analysis adds the costs of maintenance and the cost of lost wafers due to reliability failures to the initial cost of equipment and divides by the total number of wafers produced. Equipment which has a higher initial cost, but has a substantial reliability advantage and higher utilization capability, will have a lower total cost of ownership. Therefore, using this method encourages procurement organizations to invest in manufacturing capability wisely.

Research shows that on average, the initial cost of equipment only represents 40% of its total cost[1]. As a result, procurement teams at Intel have begun to focus on maintenance, spares usage, and process reliability more than ever. As the total cost of capital equipment rises, this emphasis grows in importance.

Switching to a total cost approach is not easy; it often requires a multifunctional, holistic approach that bridges organizational as well as corporate boundaries. Internal

---

[1] This data was collected from projected equipment cost of ownership models from Intel's latest equipment technology generation.

organizational boundaries must be bridged in order to capture the expertise scattered throughout engineering and manufacturing organizations. While process engineers are experts in process characterization and control, industrial engineers have expertise in determining equipment utilization. Finance develops cost accounting principles and measurements. Yield engineers focus on quality improvements and process refinements. All of these functions must work together to improve manufacturing process design.

It is equally important to capture the expertise of capital equipment manufacturers. Since the process equipment performance determines cost effectiveness, equipment design experts play a vital role in total cost reduction. In the last decade Intel has shifted in-house process design responsibility to equipment suppliers. In some cases equipment suppliers have total responsibility for maintenance as well, giving these organizations an increased opportunity for organizational learning. Thus, in many cases equipment design experts reside at key suppliers.

As a result, supplier partnerships can play a key role in the success of improvement projects. This is not only true for continuous improvement activities, but also for proactive improvements in the equipment design stage. For this reason, Intel's capital acquisition department can play a key role in determining the total equipment cost, even before contract negotiation.

There are several reasons why it makes sense to encourage incremental cost improvements at the equipment design stage. The first and most important reason is that 70% of the life-cycle cost of equipment is determined when the equipment is designed, and only smaller incremental improvements can be made after equipment installation. Equipment design determines the type and cost of consumables and replaceable parts, the time it takes to perform routine maintenance, and the frequency of required maintenance. Each of these factors can contribute to the cost of maintaining equipment.

The second reason why improvements should be made at the equipment design stage is that before equipment shipments the factory has the ability to reduce capital requirements, and thus reduce costs. Improvements to throughput and utilization capability will have less of an impact after ordering and shipment.

Change control processes also encourage improvement at the beginning stages of technology development, before equipment is installed in a factory. Since production is not affected, engineers at Intel have more flexibility to make changes early in a process technology life, adjusting for processing differences if necessary. They also have the ability at this stage to fully test a proposed improvement and determine long term reliability estimates.

In addition to these benefits, suppliers will be more likely to be partners in change decisions at the design stage. Part of the reason for this can be explained by the system dynamics model identified by Fine[2] which depicts customer and supplier relationships as an oscillating function between high and low customer satisfaction. High customer satisfaction occurs right before a contract negotiation, when the customer has the most leverage. Once a supplier receives a long term contract, their incentive for improvement is reduced. Customer satisfaction may begin to drop, since suppliers may become less responsive to customer requests. As new contracts come up for bid, the supplier again has an impetus for improvement in order to win a new contract, and the cycle repeats.

Another reason why suppliers may be more likely to be partners in the design phase is that they can react more easily to customer requests and design changes before their equipment is in production. Costs for changes will be substantially lower since changes can be incorporated before equipment delivery; suppliers will be less likely to incorporate changes after design specifications have been negotiated, and may charge a penalty to do so.

There is an added benefit to involving suppliers in cost reduction efforts in the equipment design phase. If suppliers are partners in the development of total cost numbers, Intel will have a better chance of negotiating performance agreements. Performance agreements enable Intel to share responsibility for the equipment life cycle costs with suppliers,

---

[2] Fine, Charles <u>Modeling Customer-Supplier Relationships.</u> Presentation, 1994.

charging suppliers when actual performance is lower than supplier quotation. This approach encourages reasonable forecasting during the quotation stage of a negotiation, and reduces risk for Intel.

1.1 Project Results: A Total Cost Reduction Methodology

This thesis presents the results of a six month internship at Intel in the Corporate Capital Acquisition Department. The purpose of the internship was to identify a methodology for reducing the total cost of equipment, preferably in the equipment design stage. I decided to focus on equipment spare part quality and reliability, since failures of spare parts can have a dramatic impact on the utilization capability of equipment, and wafer yield.

After working with several equipment spare part improvement teams, I found that there were many tools available for root cause identification and part redesign. The void in formalized tools appeared during the decision phase of these projects. After data collection, there appeared to be a lack of formal procedures and processes to make total cost decisions. Although portions of total cost models existed throughout Intel, they often had to be modified or adjusted for each team. This customization used valuable resources and introduced variation into the decision making process.

In addition, teams did not have a formalized approach to consider important qualitative information during the decision phase of the project. Since the capital acquisition department was evaluating new sources of material, analyzing supplier process and collecting other non-quantifiable data, a tool which could help to evaluate the significance of findings would be valuable.

The *Equipment Change Impact Model*, the main deliverable described in this thesis, was developed to help improvement teams make better decisions regarding process equipment improvements. Although this model was constructed for the semiconductor process at Intel, the ideas and algorithms of the model can be applied to a wide range of industries and can be easily incorporated into a generic improvement project roadmap.

The model includes two sections: a Financial Impact Worksheet to help teams to assess the financial implications of making a change and a Qualitative Analysis Worksheet to evaluate non-quantifiable data. The capabilities of the Financial Impact Worksheet include: a cost of change section, which helps teams to evaluate the resources necessary to make a change; a financial summary section, which calculates the Net Present Value and payback period for making change; and sensitivity analysis, which calculates a best and worst case scenario for the proposed change. The Qualitative Analysis Matrix converts team perceptions about a variety of issues into a numerical score, and compiles the scores, giving more weight to high importance issues. This combination of financial and qualitative analysis allows teams to incorporate the range of data types available to make decisions in a controlled and repeatable fashion from project to project.

This thesis outlines a process for making total cost improvements, describes tools available to facilitate this process, and introduces the *Equipment Change Impact Model*. Chapter 2 describes the important steps included in a process improvement roadmap, which include identifying cost reduction opportunities, generating root cause solutions, prioritizing improvement effort, and making team decisions regarding change implementation.

Chapter 3 provides more information about root cause analysis, which should precede the design making steps of the improvement process. This chapter also presents a case study of a unique implementation of Failure Mode and Effects Analysis, or FMEA, which identifies the root causes of a spare part failure at Intel.

Chapter 4 introduces the *Equipment Change Impact Model* and the basic total cost algorithm included in the model. Chapter 5 and Chapter 6 describe the Qualitative Analysis Matrix and the Financial Impact Worksheet respectively. Chapter 7 presents several case studies as an explanation of how the *Equipment Change Impact Model* can be used to facilitate an improvement project effort. Finally, Chapter 8 summarizes the limitations of the model and provides suggestions for future research in this area.

Chapter 2

Process Improvement Overview

One of the most interesting aspects of my internship at Intel was the exposure I had to various improvement teams from around the company. After working with a few teams, and interviewing others, I found that they were following similar steps to implement improvements. The purpose of this chapter is to provide a generic framework which encompasses a variety of improvement approaches, preserving the best practices I saw at Intel, while incorporating some suggestions for improvement.

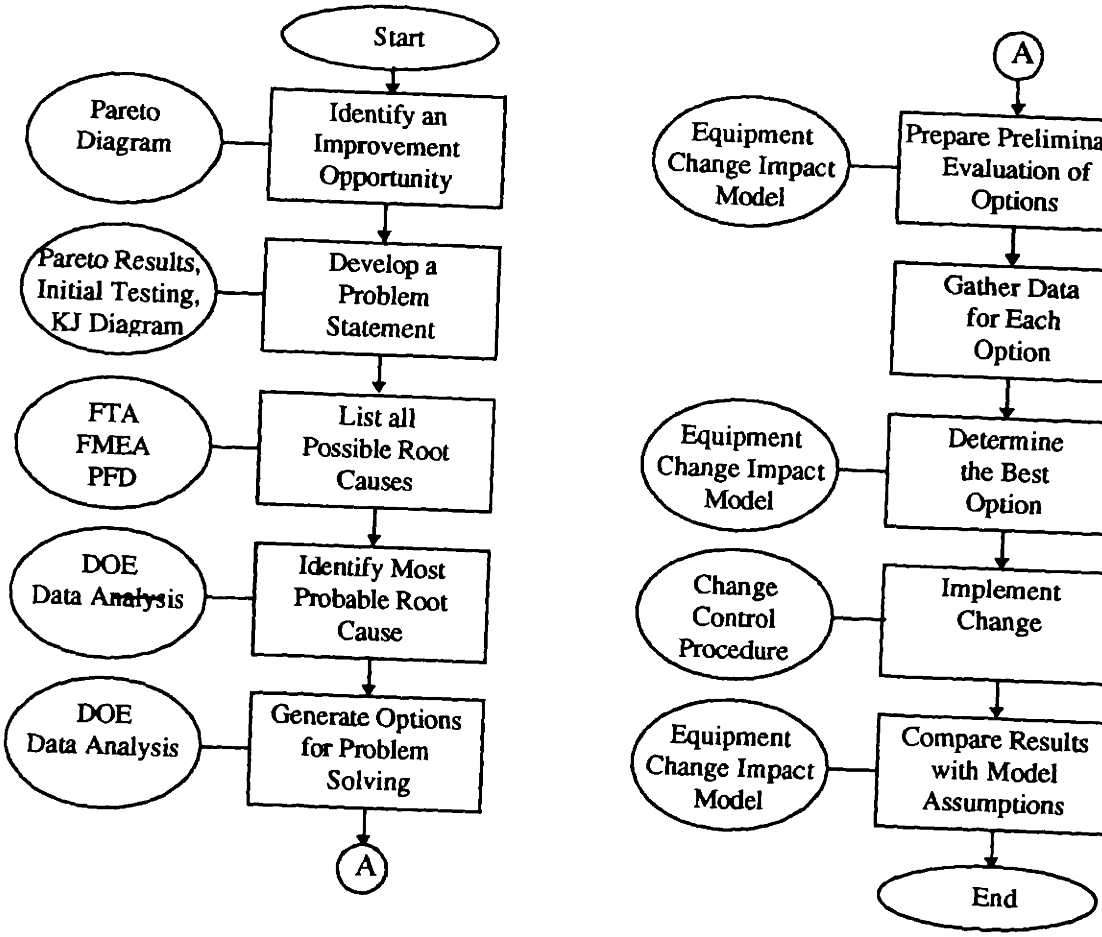


Figure 2.1: Process Improvement Roadmap

2.1 Process Improvement Roadmap

The process improvement roadmap, shown in Figure 2.1, shows the major steps in an improvement project. The circles attached to the rectangular steps in the process roadmap list examples of tools which are available to facilitate each step. This flowchart format allows flexibility in tool choice for the user, yet highlights key steps which can help organize the improvement process and can lead to an optimal solution. The following sections describe each individual step.

2.2 Step 1: Identify an Improvement Opportunity

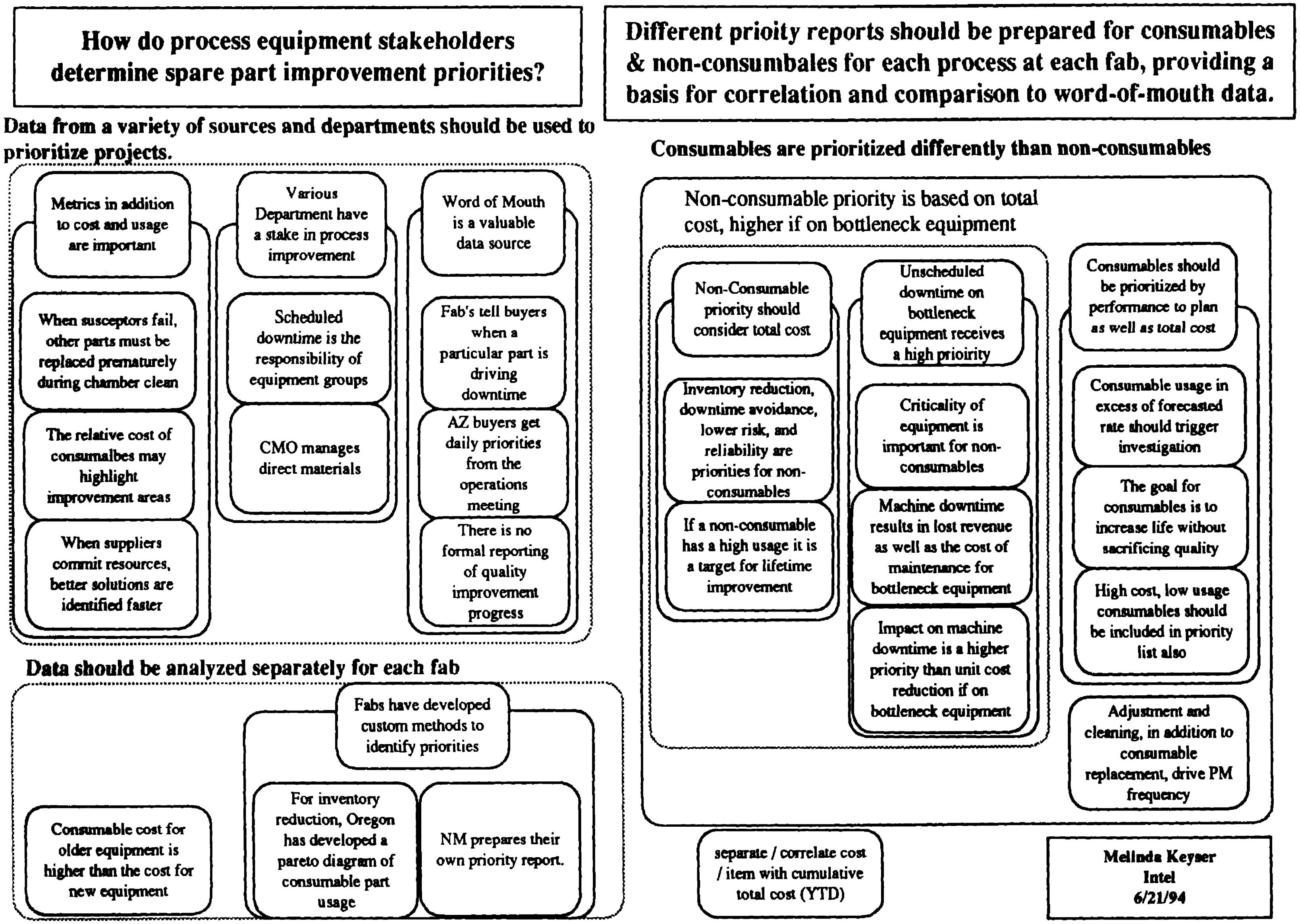
The first step for any improvement team is to identify an improvement area. At times this step will be completed before a team is assembled, as in the case of reactive process improvement. A catastrophic failure that inhibits production is an example of a high priority case when a team may assemble with a specific agenda. Continuous improvement teams or quality circles, on the other hand, may need to seek out a project to investigate and improve. For these teams, identifying an improvement opportunity is not as straightforward. To maximize the impact of their effort, teams should identify relative priorities for process improvement within the plant.

In order to benchmark current practices at Intel for determining priorities, I interviewed several managers and improvement team members. Figure 2.2 summarizes the results of these interviews in the form of a KJ diagram. This diagram helped to synthesis the opinions and experiences of all of the interviewees and resulted in a key list of recommendations.

2.2.1 Use unit cost times consumption of spare parts as a cost metric for comparison

As stated in the previous chapter, spare parts used in the semiconductor industry can account for a substantial amount of process equipment cost over the lifetime of the equipment. With this assumption in mind, a simple analysis tool for establishing project

Figure 2.2: KJ Diagram



How do process equipment stakeholders determine spare part improvement priorities?

Data from a variety of sources and departments should be used to prioritize projects.

Metrics in addition to cost and usage are important

When susceptors fail, other parts must be replaced prematurely during chamber clean

The relative cost of consumalbes may highlight improvement areas

When suppliers commit resources, better solutions are identified faster

Various Department have a stake in process improvement

Scheduled downtime is the responsibility of equipment groups

CMO manages direct materials

Word of Mouth is a valuable data source

Fab's tell buyers when a particular part is driving downtime

AZ buyers get daily priorities from the operations meeting

There is no formal reporting of quality improvement progress

Data should be analyzed separately for each fab

Fabs have developed custom methods to identify priorities

For inventory reduction, Oregon has developed a pareto diagram of consumable part usage

NM prepares their own priority report.

Consumable cost for older equipment is higher than the cost for new equipment

Different prioity reports should be prepared for consumables & non-consumbales for each process at each fab, providing a basis for correlation and comparison to word-of-mouth data.

Consumables are prioritized differently than non-consumables

Non-consumable priority is based on total cost, higher if on bottleneck equipment

Non-Consumable priority should consider total cost

Inventory reduction, downtime avoidance, lower risk, and reliability are priorities for non-consumables

If a non-consumable has a high usage it is a target for lifetime improvement

Unscheduled downtime on bottleneck equipment receives a high prioirity

Criticality of equipment is important for non-consumables

Machine downtime results in lost revenue as well as the cost of maintenance for bottleneck equipment

Impact on machine downtime is a higher priority than unit cost reduction if on bottleneck equipment

Consumables should be prioritized by performance to plan as well as total cost

Consumable usage in excess of forecasted rate should trigger investigation

The goal for consumables is to increase life without sacrificing quality

High cost, low usage consumables should be included in priority list also

Adjustment and cleaning, in addition to consumable replacement, drive PM frequency

separate / correlate cost / item with cumulative total cost (YTD)

Melinda Keyser
Intel
6/21/94

improvement priority is a pareto diagram[2] comparing the unit cost of every spare used in the factory multiplied by its usage. Although there are drawbacks to this approach which will be discussed further in this chapter, this data is often readily available, and the analysis can be done quickly and effectively.

2.2.2 Separate data into comparable groupings for pareto analysis

A pareto analysis is an excellent tool for comparing data in order to prioritize effort. The validity of the pareto diagram results is extremely dependent on method used to sort the data. It may not make sense to compare data across an entire factory, or an entire parts list, since the data may have distinctly different characteristics.

For instance, replaceable parts for equipment can be grouped into two categories. One is consumables; those parts which are consumed by the process and must be routinely replaced. Although the definition of a consumable has been highly debated among equipment suppliers, a common definition that is based on the predictability of replacement is beginning to emerge. Thus, gases, parts which contribute material to a process like targets in a sputtering operation, and other parts which are changed during routine maintenance often fall into this category. The expected lifetime for these parts is often predicted by the equipment supplier. Stocking levels are then determined by the lifetime prediction and planned factory throughput. As the throughput rate increases, the quantity of consumable parts needed to sustain the process increases.

By contrast, non-consumable usage reflects the reliability of the equipment. Since non-consumable usage is often unplanned, replacement of these parts is usually done during an unscheduled maintenance step. This failure can result in excessive downtime, especially if the part is not stocked in a local warehouse. Usually these types of failures also result in a

---

[2] Although this thesis does not describe how to do pareto analysis, descriptions can be found in many TQM resource books, including Ishikawa, Kaoru. Guide to Quality Control. Tokyo: Asian Productivity Organization, 1982.

loss of wafers, since many unexpected spare part failures occur within a process chamber during processing.[3]

Suppose a pareto diagram is completed to compare the unit cost times consumption of all spare parts, regardless of category. The consumables would most likely float to the top of the pareto list, since by definition they are used much more frequently than non-consumables. Non-consumables, however, may represent a higher priority for improvement based on their total cost impact. For these reasons, separate pareto diagrams will help teams to compare similar parts with similar usage patterns and factory impacts.

Another category worthy of separation in pareto analysis is the technology generation. Older factories at Intel have less complicated and, as a result, less expensive process equipment. Newer factories, in general, are running more sophisticated and costly equipment. If spare part unit cost times consumption is compared across factories, it is likely that all improvement projects will be focused on the newest technologies.

There are two problems with this approach. The first and less important problem is that newer factories focus on ramping production and characterizing the process for the first time; they may not have the time or resources to engage in improvement projects. Older factories, however, have long since perfected their processes and can concentrate more resources on improvement efforts. More importantly, older factories tend to have much lower profit margins than newer factories.[4] This gives them a higher impetus for improvement for cost reduction projects than older factories. For this reason, a more balanced effort on cost reduction should be implemented across factories. In order to do this, pareto analysis should be separated for each process technology, ensuring that priorities will surface for older factories as well as newer factories.

---

[3] Intel uses the term "line yield loss" to describe wafers that are damaged during production and "line yield" is the percentage of wafers which can be made into microprocessors to sell. A similar term, "die yield," is the percentage of good die, or microprocessors, on each wafer.

[4] The profit margin difference between newer and older semiconductor facilities arises from the quick price erosion in the microprocessor market. Newer factories often produce the latest technology, which has a higher price. As the price quickly drops for new technology, the margins in the newer factories will also decrease.

Figure 2.3 shows the results of a pareto diagram for two separate factories at Intel. These diagrams show the unit cost times consumption for all spares used at two different factories. Only the top six spare parts for each of the factories are shown in these diagrams. Since there is not a system in place today at Intel to separate consumables from non-consumables, these paretos were prepared using all spare parts regardless of category distinction. Notice that susceptors, spare parts used in Chemical Vapor Deposition (CVD) equipment, rise to the top of the pareto for Factory "A" and are among the top few spares for Factory "B." By choosing this spare to improve, there is a potential for improvement in more than one factory.[5] Chapter 3 will revisit the susceptor failures, and describe the root cause analysis that was conducted at Intel.

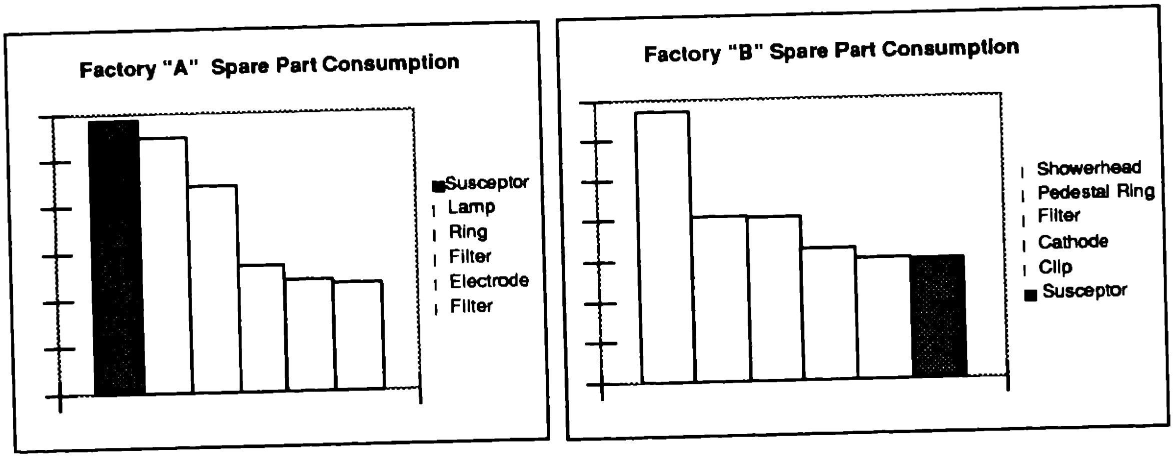


Figure 2.3: Unit Cost * Consumption Pareto Diagrams

2.2.3 Sort non-consumable parts using total cost metrics

The analysis presented so far have made an assumption that unit cost times consumption is the highest priority for Intel. The downside of accepting this assumption is that other cost factors, like downtime or yield impacts can be as expensive or more expensive than the initial cost of the spare parts. High reliability spare parts may last much longer, or improve line yield, which may justify their high initial costs.

Total cost is an alternative measure that can be used to compare the impact of spare part cost as well as downtime, yield, and reliability costs. This measurement, which will be

---

[5] The susceptor will also be discussed in Chapter 3, which describes root cause identification of a problem.

explained fully in Chapter 4, divides the costs of making wafers by the number of wafers produced by the equipment. This results in a cost per wafer metric which can be compared across a factory.

Figure 2.3 shows one possible approach for creating a pareto diagram based on total cost. This pareto compares the planned cost per wafer for all equipment used at one factory. Process Equipment "A," which creates the highest cost for the factory, rises to the top of the pareto. Consumable cost, which is also shown on the pareto is a small percentage of the cost of process equipment "A." This raises other issues for the team: perhaps the biggest opportunities reducing process step costs is downtime reduction, reliability improvement, or other process improvements. If the team decides to tackle process "A" for improvement, they should continue with the process improvement roadmap and use the next step of problem identification to further define the team objective.

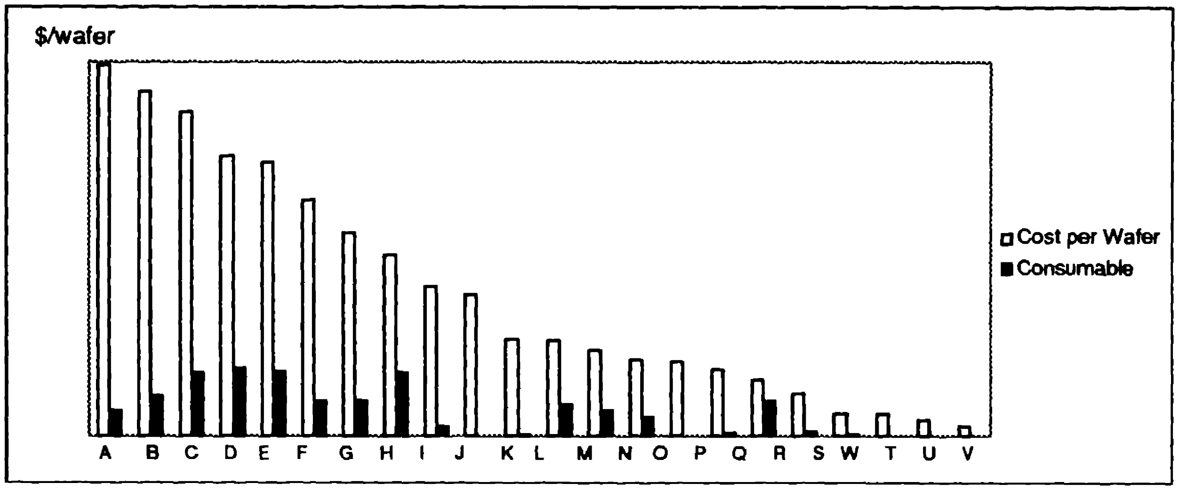


Figure 2.4: Planned Cost Per Wafer for Factory "A

2.2.4 Sort consumables using performance to plan as well as total cost

Figure 2.4 shows the planned equipment costs as quoted by the equipment suppliers. This pareto could be used in the future as a benchmark for actual production. Once equipment is installed and running, the factory can compare actual results with the plan to identify areas where the actual costs exceed the plan by a substantial amount.

In order for this technique to be useful, Intel must ensure that the initial cost forecasts are realistic and approved by the equipment suppliers. This allows future teams to use the cost delta information to identify unexpected process weakness. In cases where Intel has contracted maintenance support along with equipment purchases, the delta may point to a maintenance issue, or highlight a potential contract weakness.

2.2.5 Prioritize bottleneck equipment improvements

So far all equipment sets have been considered to be of equal importance for process improvement. This may not always be true, especially for Intel where many factories are capacity constrained. In these cases, one equipment set is a factory output limiter since its throughput is less than all other equipment sets in the factory. As described by Menon[6] , these factory limiters, or bottlenecks, deserve a higher priority for process improvement. Improved throughput in these areas directly translates to increased revenue. His fully describes methods for prioritizing improvement projects using this approach.

2.2.6 Other considerations

There may be other considerations when choosing an improvement project. Some new teams may want to start with a relatively simple project, in order to establish team dynamics and accomplish an early win. This often helps to improve morale and encourage teams to continue with improvement efforts.

Another consideration for teams is the amount of supplier interface necessary and the exiting relationship that the company has with the supplier. The quality of the supplier involvement can impact the quality of team results substantially. If there is a positive working relationship with a supplier and the supplier agrees to participate, the project has a higher chance of success. On the other hand, since problem solving can improve communication across organizations, a company may want to embark on a project with a supplier with which there are few established relationships, with the sole purpose of

---

[6] Menon, Viju S. "A Constraint-based Systems Approach to Line Yield Improvement in Semiconductor wafer Fabrication." Masters Thesis MIT, 1994.

fostering teamwork. Either way, a team should consider these aspects before beginning a project.

Finally, the human resource investment that occurs when embarking on a project may be a consideration. An improvement project can provide a catalyst for team members to learn and apply new skills, such as statistical analysis, or specific technical knowledge. If there are several products which use similar technologies, the specific knowledge gained by the team can be applied easily to similar problems in the future. This increase in employee knowledge, therefore, can provide a future productivity advantage in the future.

2.3 Develop a Problem Statement

The next step in process improvement is preparing a problem statement. This step can be a critical, since it defines the problem at hand and provides project focus. Determining the correct problem may appear to be an easy task, but can often entail two or three brainstorming and data collecting iterations before the correct problem becomes evident.

The most important point for teams to remember at this stage is that a problem should be reduced to the lowest level possible to facilitate root cause analysis. A case study observed at Intel will help illustrate this point.

2.3.1 Spare Part Improvement Project

One team I observed at Intel had identified a problem with an equipment set. One of the

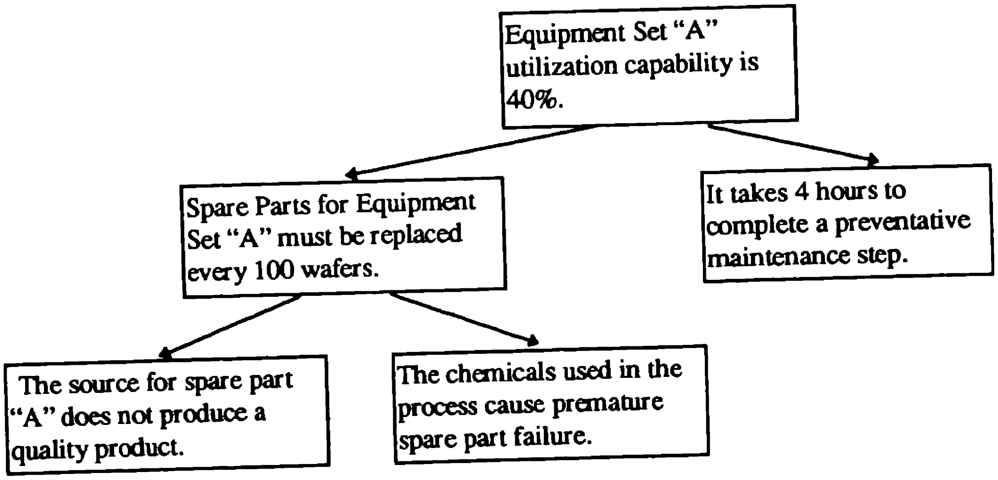


Figure 2.5: Iterative Problem Statement Definition

spare parts used by the machine was failing after a few hundred wafer passes, causing a high replacement rate, and low machine availability. The initial team could have developed a problem statement "Equipment Set A utilization capability is 40%" (See the top node of Figure 2.5.) With this problem statement in mind, the team would have many possible root causes to identify. One approach would be to increase the time between spare part replacement in order to improve utilization. Figure 2.6 shows the positive effect this improvement would have on the wafer pass per week capability.

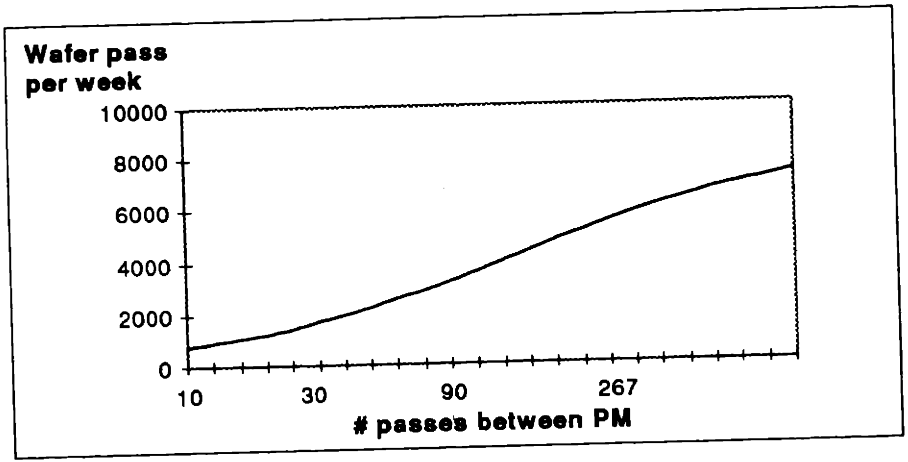


Figure 2.6: Effect of Increasing Spare Part Life on Throughput

As shown in Figure 2.7, this would also have a positive effect on availability, increasing it to nearly 80% while decreasing the PM frequency proportionally.

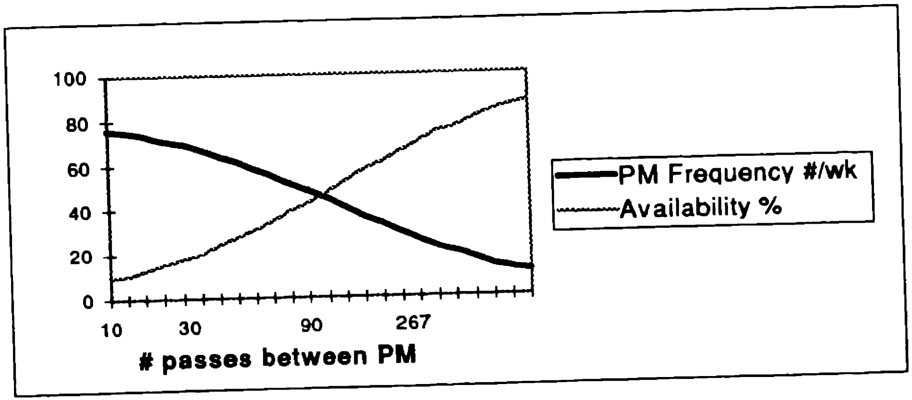


Figure 2.7: Effect of Increasing Spare Part Life on PM Frequency and Availability

The problem statement "Equipment Set "A"" utilization capability is 40%" could also have resulted in an effort to decrease the actual time it takes to perform a PM step. As Figure 2.8 shows, this improvement would also increase the wafer pass per week throughput. Unfortunately, it has a very different effect on availability, decreasing availability to less than 40%. This is due to the increase in PM Frequency. As less time is spent performing PMs, more time becomes available to process wafers, increasing the number of PMs which must be performed.

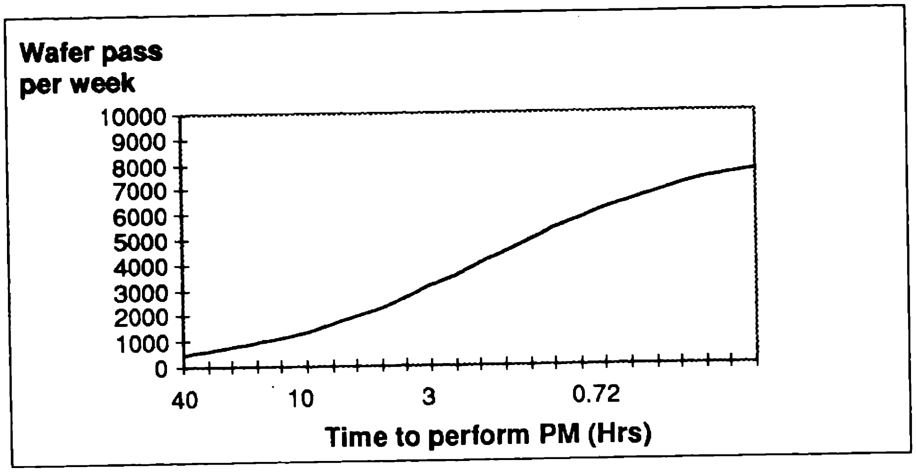


Figure 2.8: Effect of Decreasing PM Time on Throughput

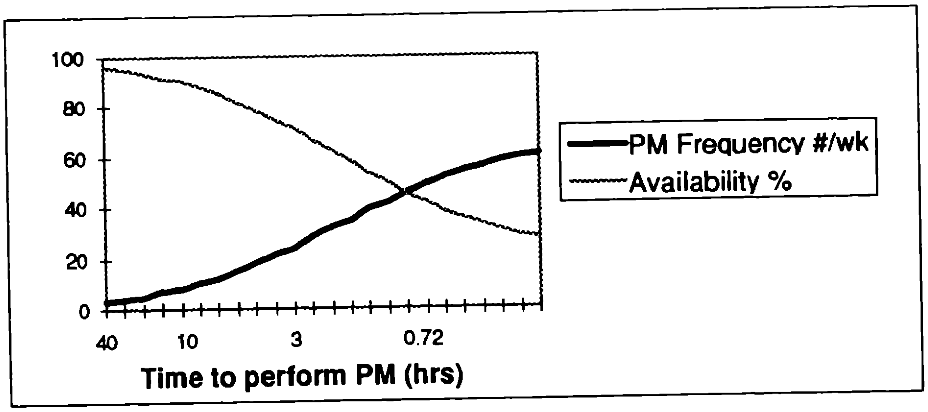


Figure 2.9: Effect of Decreasing PM Time on PM Frequency and Availability

Thus the original problem statement is not specific enough and should be rewritten as "Spare parts for Equipment Set "A" must be replaced every 100 wafers." This statement identifies the problem, yet still provides latitude for the creative problem solving. If the team settled on a more specific problem statement, like "The source for spare part A does not produce a quality product," the team is making an assumption before gathering data. The team may also block out the possibility of a process equipment change to improve the spare part performance.

In the above example the team must continue to collect data and rewrite the problem statement until satisfied with the direction of the project. This iterative approach encourages brainstorming and helps the team to arrive at a consensus.

2.4 List all Possible Root Causes

After the problem statement has been generated, the team is ready to brainstorm for possible root causes. The risk at this stage of process improvement is that teams may jump to a conclusion about the specific root cause without collecting data. To avoid this outcome teams should use tools like Fault Tree Analysis (FTA), or Failure Modes and Effects Analysis (FMEA), to identify all possible root causes. By using this type of process many teams will uncover a potential root cause that was not obvious before the brainstorming activity. Chapter 3 describes how the FMEA can be used during this step in the improvement process and explains how one Intel team benefited from this approach.

2.5 Identify Most Probable Root Cause

Once all possible root causes have been identified, the team must collect data in order to verify the most probable root cause. The complexity of the problem will dictate the level of analysis that is necessary at this stage; available tools range from simple attribute data collection and control charting to sophisticated Design of Experiments (DOE). This data collection step confirms initial team findings and helps the team to generate solutions.

2.6 Generate Options for Problem Solving

After detailed statistical analysis, the team moves to problem solution. At this stage, the team may identify more than one approach for solving a problem. The options may include various changes, including second sourcing options, equipment redesign, spare part design changes, or process modifications. At this stage the team should be encouraged to generate as many options as possible.

2.7 Prepare Preliminary Evaluation of Options

Although the team has identified several methods for improvement, they may not have the resources available to consider all of the options at once. At this stage the team should evaluate the options using qualitative data, if quantitative data does not exist. The *Equipment Change Impact Model*, which will be described fully in Chapters 4 through 9, can be used at this stage. The first worksheet in the model is a qualitative analysis matrix, which can be extremely valuable at this stage of the project for determining team priorities. The Financial Impact Worksheet, the second worksheet in the model, can also be used at this stage to approximate the savings and costs of making each of the proposed change, and point to areas where additional data gathering is necessary.

2.8 Gather Data for Each Option

After establishing clear priorities, the team must gather data for each option. The purpose of the data collection step is to verify the feasibility of each improvement option. At times this testing is completed by the supplier; in other cases the change must be tested in the actual operating environment. The data which is collected in this phase may also be collected in accordance with change control procedure. Chapter 5 describes the change control procedure at Intel. The time and resources necessary to complete this step are captured in the "Cost of Change" section of the *Equipment Change Impact Model*. Often the amount of data that is necessary is based on the amount of risk inherent with implementing a change.[7]

After gathering data the team may determine that the change is not feasible, or that additional design adjustments must be made. In this case, the team should return to the "Generating Options" step. Otherwise, the team can progress to the next step to determine the best option.

2.9 Determine the Best Option

In order to determine the best option the team must come to a consensus. After working with several teams at Intel, I found this to be a particularly difficult step. Many teams had developed analytical tools to help them with this step, but each team had a slightly

---

[7] An excellent definition of equipment changes and an explanation for the need for change control can be found in Mares, Moses. Equipment Change Control. Austin: SEMATECH, Inc.,1992.

different approach. If a supplier was involved in the process improvement, the step became even more complicated.

The *Equipment Change Impact Model* was developed to capture the best practices throughout the organization, and provide a generic analysis tool to make this step easier. The Financial Impact Worksheet, included in the model, gives teams a realistic look at the impact of the project financially and can help teams decide whether to implement a change. If more than one option is being considered, the *Equipment Change Impact Model* can help to determine which option has the highest financial return.

2.10 Implement Change

At this stage, the team implements the proposed change. Since Intel, like many firms, have well developed change control procedures, additional testing or documentation may be required.

Teams should consider all aspects of change implementation, including inventory stocking, part number changes, factory support, and training. There may be additional concerns based on the type of change being made.

2.11 Compare Results with Model Assumptions

The final step in the improvement process is to collect data after implementation. This allows teams to verify actual results and compare them to the initial testing results and the key assumptions made in the *Equipment Change Impact Model*. This provides a final check to make sure that the change was executed correctly. It also verifies that the initial problem statement has been addressed and that the root cause of the problem has been eliminated. Once this step has been completed, teams can celebrate and move on to the next improvement priority.

The following chapters provide additional detail about the root cause identification step, as well as a full explanation of the *Equipment Change Impact Model*.

Chapter 3

Root Cause Analysis

One of the most critical steps in an improvement project is root cause identification. The identification of a root cause helps teams to formulate a solution which will address the systemic reasons for the problem at hand and prevent reoccurrence. Root cause identification is not easy, however, and many teams can loose focus during this step. This chapter explores possible reasons why root cause analysis is so challenging and presents several tools which have been used by teams in the past to facilitate this process. The chapter also describes the Failure Modes and Effects Analysis, or FMEA in detail. This tool, which is traditionally used during initial design verification, can also be used successfully for problem solving. The chapter concludes with a case study of how the FMEA was used by an Intel improvement team to prioritize efforts and surface a potential root cause for the first time.

3.1 The Challenge of Root Cause Identification

While benchmarking improvement teams across Intel it became immediately apparent that identifying breakthrough solutions was not easy. Part of this is due to the complexity of Intel's process and equipment design. Many teams had been in existence over 2 years without reaching a conclusion. Other teams had implemented changes only to find out that a problem reoccurred. In these cases a team had overlooked a root cause and addressed a symptom instead.

These scenarios are not unique to Intel, but exist universally. This section details several reasons why this step is especially difficult to complete.

3.1.1 Teams often jump straight to a conclusion, without understanding the root cause.

When a major problem surfaces, teams are not always measured by the quality of the solution, but by the speed of solution implementation. Many managers have built a career on the ability to assess a problem quickly and provide a solution There is also an emotional appeal to identifying a solution; teams feel as though they are making progress and are excited to be finished with one project in order to move on to the next. For this reason, they may stop investigating the situation too soon. The risk of rapid implementation of a solution is that the systemic root cause of the problem may have been overlooked, and the problem can easily reoccur.

3.1.2 The knowledge needed to properly identify the root cause often lies across organizational boundaries and across companies.

The root cause of a problem is not easily identified; often it takes expertise of several different functional members to identify all the possible causes for a problem. As more and more critical processes are supplied by outside specialists, improvement teams need to solicit valuable expertise from other companies. This adds complexity to the problem solving process as well as logistical challenges.

3.1.3 The process is tedious and can be time consuming.

Unless problem solving is a priority for all of the team members, identifying the root cause can drag on for several months. Since the process involves detailed data collection, team members who prefer action-oriented tasks can be disillusioned.

3.1.4 Often there are many possible root causes for a problem.

As discussed later in this chapter there may not be enough resources available to fully investigate every possible root cause for a given problem. If teams do not systematically prioritize tasks, their effort can be too diluted to be effective, or they can miss a critical root cause.

3.2 Root Cause Analysis Tools

Fortunately, there are several tools available to facilitate the root cause identification phase. The easiest to learn and to understand are the 7 QC tools used in the Total Quality Management (TQM) process.[8] These are:

- check sheet/stratification
- Pareto diagram
- cause-and-effect diagram, also called the Ishikawa diagram or fishbone diagram[9]
- graphs
- control charts
- histogram
- scatter diagram

Although these tools are very good for initial analysis, there are cases where further analysis is necessary. This can occur when the process technology is not fully understood, or when these tools generate confusing results. The next section describes another tool which helped an Intel improvement team arrive at a more systemic approach to problem solving.

3.3 The Failure Modes and Effects Analysis (FMEA)

This tool is primarily designed for initial product design and process development in order to investigate all potential failure modes and mechanisms and ensure proper protection is in place for failure prevention. Though it is an excellent tool for proactive analysis, it can also be used quite effectively for problem solving or for strategic process improvement. One of the reasons why the FMEA is so effective for these types of applications is that the tool requires cross functional brainstorming in order to complete it sufficiently. This helps a team to gather and share information and often will trigger a new concept or idea during the formulation process.

---

[8] A brief summary of each of these tools can be found in Shiba, Shoji. A New American TQM. Cambridge: Productivity Press, 1993. Complete descriptions of these tools can be found in Ishikawa, Kaoru. Guide to Quality Control. Tokyo: Asian Productivity Organization, 1982.

[9] An alternative format for this type of diagram is the Fault Tree Analysis, or FTA. This approach, which is easier to document on the computer, will be described later in this chapter.

Preparing an FMEA requires systematic identification of potential root causes in addition to numerical data, which helps to prioritize root causes which are most likely to occur. This can help a team to focus energy and prioritize effort. Finally, the FMEA format provides one cohesive look at a problem which can help to facilitate future communication and cooperation, especially if a problem solving team spans organizational boundaries.

Failure Mode	Cause(s)	Occurrence	Effects	Severity	Safety	Current Controls/Fault Detection	Protection	RPN	Recommended Actions	A.R. Owner
Anodize Delamination	anodize current density		Particles							
	anodize current density		Uniformity							
	broken connection between susceptors and rack, rack & cable during anodize		Particles							
	broken connection between susceptors and rack, rack & cable during anodize		Uniformity							

Figure 3.1: FMEA Format

Figure 3.1 shows a partially completed FMEA used by a joint Intel-supplier team to identify the potential root causes of a high failure rate spare part. The purpose of the first column is to list all possible failure modes. FMEA users are encouraged to record all possible modes even if they seem less possible. Once all of the failure modes for a product have been identified, the potential root causes are recorded along with the effect that a failure mode can have when it occurs. In some cases, as in the example illustrated in Fig. 3.1, there can be more than one effect for every root cause. A team should record as much detail as necessary to fully understand the problem. As will be explained later in the chapter, detailed information proved vital to the success of one Intel project.

The next brainstorming step is to identify the controls in place which would prevent a root cause from surfacing. In order to get this information, the team may need to contact a supplier, or in some cases a supplier's supplier or sub-contractor, in order to identify the controls in place. For this reason it may be beneficial to have engineering and/or manufacturing representatives from a supplier's organization as team members. The process controls are listed in the "current controls/fault detection" column of the FMEA.

Once the failure mode, root cause, effect, and current control information is recorded, the team collects data on how frequently each failure mode occurs and uses the "occurrence" column to record a relative ranking, with the highest numbers representing the highest occurrence rate. The team then uses the severity column to rank the impact that a failure mode will have in the factory, using the highest number to represent the worst possible impact. Finally the team assigns a rank to the controls in place, placing a higher score on areas which do not have sufficient process control in place to prevent failure. The RPN, or Relative Priority Number, is the product of the occurrence, severity, and control rankings. The RPN can then be used to highlight those failure modes with the highest chance of occurring, the greatest negative impact to the factory, and the least amount of process control in place for prevention.

One of the most important things to remember when preparing an FMEA is that patience is extremely important. FMEA's "may easily consume hundreds of man-hours[10]" depending on the application. Once an FMEA format is complete, however, it can be easily updated to track team progress and can be modified for similar products to reduce the resource requirements of future FMEA analysis.

A second important point is that the benefit of performing an FMEA is not the document itself, but the understanding and communication it promotes. By going through the process of preparing an FMEA, team members have a heightened awareness of potential failure modes, and have a clear understanding of a problem complexity.

Finally, an FMEA is not a substitute for other Total Quality Management tools, but should be used as a roadmap to establish a priority for problem solving. Specific tools, like Design of Experiments, or other analysis techniques may then be necessary in order to reduce the occurrence, severity, or impact of a failure mode. After implementation of a

---

[10] Hatty, Mark. "Potential Failure Modes and Effects Analysis: A business perspective." Quality Engineering 7.1 (1994-95): 169-186

solution, the FMEA can be used again to make sure that important issues have been addressed.

3.4 Susceptor Core Team Example

Due to an abnormally high failure rate in Chemical Vapor Deposition, or CVD, equipment at Intel, a cross functional task force was formed to identify the root cause of the failures and implement a solution. The failure mode observed was a high particle rate and an abnormal thin film uniformity. After a detailed process of elimination, the susceptor, a spare part used in the process chamber, was identified as the source of particles. The susceptor, which is shown in Figure 3.2, supports the wafer during thin film deposition.

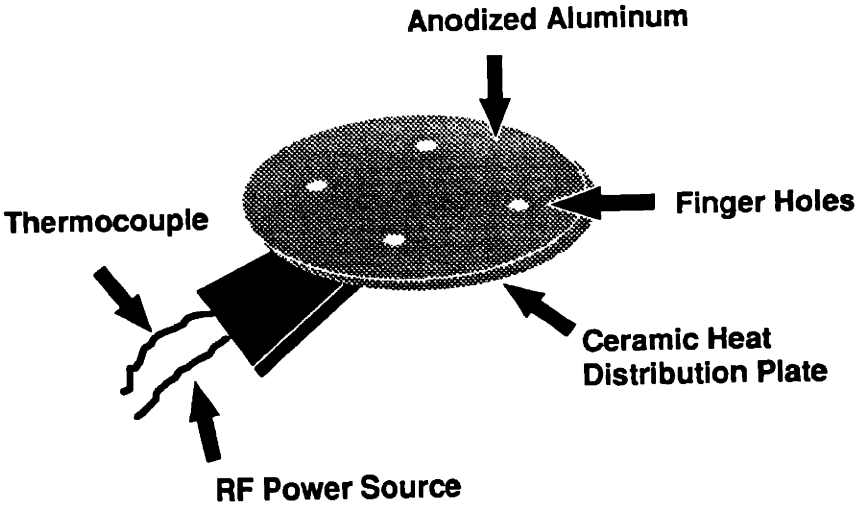


Figure 3.2: Susceptor used in CVD process

Its purpose is to create an electrical contact with the silicon wafer as well as maintain a uniform temperature during the deposition process. The base material for the susceptor is aluminum bar stock, with an anodized coating. The susceptor surface is flat with the exception of a tightly radiused lip, which serves as a positioning mechanism for the wafer. Four holes, called finger holes are machined in the plate to allow four separate lifts to extend through the susceptor to lift the wafer toward the top of the process chamber during a backside etching process.

The arm of the device connects it to the process chamber and is positioned and leveled after installation. Two wires extend from the arm: one is a thermocouple to monitor and control the susceptor surface temperature. The other is an RF power source. Removal of a susceptor and replacement is performed on a routine preventative maintenance schedule determined by Weibull analysis data. This replacement is performed during every other wet clean process, and is accompanied by the replacement of other parts. The entire process for a wet clean and susceptor replacement takes approximately 12 hours to complete.

After a predetermined number of wafers have been processed through the CVD equipment a process check, called a monitor step, is performed. A monitor step uses a non-production grade wafer, called a monitor wafer, upon which a film is deposited. The wafer is then checked for film uniformity, stress, and particles. Since some of these tests can be destructive, this type of testing is not done on production wafers. If an out-of-control characteristic is found, the CVD chamber is checked systematically to find out the source of the failure. In the case of particle failures, potential particle sources are checked and cleaned if possible or replaced. The susceptor is one of the components which may be changed to eliminate particles.

When the failure rate began to rise in the process chamber, the technicians noticed that when the susceptor was changed, the particle counts and uniformity measurements returned to normal. They also noticed that the susceptors which were removed from the process chambers had small black or white spots on them. These discolorations were termed "orange peel," or "chicken pocks," and though they were apparent visually, they did not always have a texture which could be felt. Once technicians began to see these discolorations during unscheduled maintenance steps, they began to remove any susceptor which had these discolorations during a wet clean, even if the susceptor was not scheduled to be replaced at that time and all process parameters were in control.

The increased rate of replacement for susceptors caused many problems. First, it increased the downtime of the equipment, lowering utilization and creating factory bottlenecks. Second, it caused a high spare replacement cost, since more susceptors were used than planned for, in addition to other parts which needed to be replaced at the same time. Finally it put the factory in a high risk of shutdown, since the spare part inventory levels dropped suddenly due to the high replacement rate.

The susceptor was sourced from the equipment manufacturer, although the equipment manufacturer only performed assembly and inspection operations in house. The critical processes, susceptor plate machining and anodize, were completed at subcontractors. When the susceptor core team was formed, members from process engineering groups at several fabs were gathered under the leadership of the Process Equipment Development group. The supplier representatives, who were also part of the team, were from several functional groups including marketing, engineering, and supplier quality. Most of the team meetings were conducted via teleconferencing on a weekly basis. The supplier was responsible for the meeting agenda and communicated their progress on the root cause analysis of the susceptors. In order to facilitate the root cause analysis, Intel sent all failed susceptors to the supplier for inspection.

One difficulty with the problem solving effort was that the team members did not fully understand the complexity of the base material forming at the aluminum plant, the machining operation, and the anodize process. They also left the root cause identification task solely to the supplier. After almost a year of core meetings, the team felt dissatisfied with the progress.

In order to facilitate future discussions, and perhaps gain new insight, the team decided to prepare a Fault Tree Analysis, or FTA. The FTA was compiled using a series of meetings with the engineering and manufacturing experts at Intel's equipment supplier. Since schedules did not permit one brainstorming session with all of the members in attendance, the FTA was prepared in several steps. The major portion was completed with the engineering expert. This result was then reviewed with the supplier quality manager who had been working most closely with the key suppliers. Finally the product service representatives were consulted to review the FTA. Although this approach did not make use of the benefits of brainstorming, it helped to accomplish the task in a shorter amount of time and still helped to communicate the major failure modes to the team.

The resulting FTA is shown in Appendix A. Notice that there are several layers of detail, often two or three layers deep. Since several of the root causes can result in more than one failure mode, many of the branches of the FTA are repeated. Thus, it is difficult to digest the entire fault tree upon observation. Further, it is not apparent from the diagram which branch is the most likely or has the most severe failure mechanisms. Finally, it presents no roadmap for further team progress.

3.4.1 Formulation of an FMEA

At this point in the project the team decided to transfer the results of the FTA to a FMEA format. Once an FTA has been compiled, this transfer is quite easy. The top rows of the FTA become the categories in the "effects" column of the FMEA. The middle layers of the FTA become the failure modes, and the most detailed branches are the root causes. Once this information had been transferred, data was collected to fill the other FMEA columns.

As described earlier, the "occurrence" column is used to reflect the number of times each root cause happens in the field. Unfortunately the root causes, such as a broken connection between the rack and susceptor during anodize, were not tracked through any formal data collection process. However, Intel did have data on the occurrence of the effects. After receiving several failed spare parts, the equipment supplier expert could estimate with a high degree of certainty the percentage of time a failure mode was the cause of the effect which occurred at Intel. Finally, the supplier expert could use an educated guess to determine the percentage of time that each root cause led to a given failure mode. The leads to the following equation to determine the percent occurrence of each root cause:

$$\begin{aligned} &RootCause\% = \\ &(EffectOccurrence\%)(FailureModeOccurrence\%)(RootCauseOccurrence\%) \end{aligned} \tag{3.1}$$

Figure 3.3 shows an excerpt from the completed FMEA. Notice that in this case the effect, particles, was observed in 13% of susceptor failures. When this failure mode occurred, the supplier expert found that 30% of the susceptors returned after observing this mode at Intel showed evidence of Nodules, another term for the variations in the anodize appearance explained either. Of these failures the supplier estimated that 75% were due to second phase precipitates in the base material. Multiplying these percentages together gave the percentage of the time susceptors failed for second phase base material precipitates, or 2.93%. Once all of the root causes in the FMEA were assigned a percentage the root causes were assigned a rank from 1-10, 10 being the highest occurrence percentage.

Failure Mode	Process	Cause(s)	Occurrence effects	Occurrence failure mode	Occurrence root cause	Occurrence %	Rank	Effects	Yield	Downtime	Severity	Current Controls/Fault Detection	Protection	RPN
Nodules (poppy seed, orange peel, volcanoes)	W	second phase precipitates in base material	0.13	0.3	0.75	2.925	10	Particles	6	3	9	-Chart recorder data (discrepancy could be caused by base material) -Visual difference after anodize -Chemical analysis by S&R on every purchase order (finds % of mat'l, not distribution) -Anodization rate qualification check (not formalized)	8	720

Figure 3.3: Susceptor FMEA excerpt

The severity scores were determined by estimating the yield and downtime implications of an effect. In order to do so several process engineers at Intel were asked to rate the yield and downtime. The yield implications were determined using a scale of 1-10 with 1 corresponding to no wafers affected and 10 corresponding to 50 lots scrapped as a result of this failure mode. These ranges were chosen because they represent the range of actual impact. The downtime implications of an effect were rated on a scale of 1-5, 1 corresponding to no downtime and 5 corresponding to 48 hours of downtime due to a given failure mode. The yield and downtime rankings were added to give a final severity rating. Note that the range of yield implications was twice as large as that for the downtime implications, making yield twice as important to the severity rating as yield.

Since as this point in the process over 50 root causes existed, the team decided to first multiply the occurrence by the severity to obtain in intermediate ranking on which to prioritize effort. Then the supplier was interviewed to determine the controls in place to prevent a root cause for the top 15 root causes. Finally an appropriate rank from 1-10 was assigned to the controls in place, 1 corresponding to very tight process control, and 10 corresponding to no controls in place. The occurrence, severity, and control rankings were then multiplied together and sorted to obtain the top 5 root causes.

Figure 3.4 shows the top 5 root causes of the FMEA, including a preliminary action plan for addressing the root causes. This information was then used to establish a priority for further task force effort, which included a designed experiment to address finger hole ridge formation and a base material specification revision. The entire FMEA can be found in Appendix B.

3.5 Benefits of using the FMEA for problem solving

In retrospect, the team was pleased with the results of the FMEA process, and the resulting roadmap. Preparing the FMEA had several advantages in that it:

- Provided Key Information for Task Force Prioritization
- Surfaced a Non-Resourced, High Priority Failure Mode
- Clearly Communicated Major Failures Causes Across Organizations
- Taught and Proliferated FMEA Preparation at Supplier

The major advantage of the FMEA was that it helped the team to focus their effort on those root causes which were most likely surfacing as failure modes at Intel. Since there were limited resources on the team, this prioritization let the group concentrate on the vital few with the confidence that the most important aspects of the problem were being addressed.

The process also helped to surface a failure mode and associated root cause that the team had overlooked in the past. The finger hole ridge formation, which manifested itself as discoloration, or a raised surface just around the finger holes, had previously been grouped

Failure Mode	Cause(s)	Rank	Effects	Yield	Downtime	Severity	Current Controls/Fault Detection	Protection	RPN	Short Term Action Plan (< 6months)	Long Term Action Plan
Nodules (poppy seed, orange peel, volcanoes)	second phase precipitates in base material	10	Particles	6	3	9	-Chart recorder data (discrepancy could be caused by base material) -Visual difference after anodize -Chemical analysis by S&R on every purchase order (finds % of mat'l, not distribution) -Anodization rate qualification check (not formalized)	8	720	-Evaluate "conductus" machine procurement for incoming inspection resistivity check -Develop 6061 AMAT specific spec -Formalize anodization qualification plan -Develop outside metrology service to check grain size, percipitants, distribution	-Develop/assess sourcing capability to meet new spec (plate and bar) at Alcoa, Kaiser, Teledyne, Reynolds -Develop anodize qualification check -Evaluate in-situ process control (resonant frequency) -Implement inspection on-site at base material mfr.
Anodize Delamination	anodize current density	10	Particles	7	3	10	-Current density, ramp, voltage & time intervals, and total time are specified. -Chart recorder tracks anodization rate -Inspection step compares specification with Chart recording -Applied engineer on-site to oversee process monitoring -No rework allowed	3	300	-Construction & evaluation of in-situ film thickness monitoring device -Document chart recording and process adjustment procedure -Train Anodizers to perform process monitoring step -Evaluate effect of concentration tolerance on electrolyte conductivity	-Institute real time feedback control of anodize process with in-situ process monitor -Remove on-site Applied engineer
Finger Hole Ridge Formation	anodize edge defect phenomenon	3	Uniformity	6	3	9	-Design spec in place -Inspection technique specified -Machining technique not sufficient (cannot meet spec)	10	270	-Verify current machining process causes edge defects and finger hole ridges -Determine capability of current process -Increase hole diameter to 60 mils -Evaluate electropolishing and microdeburring techniques to remove included edge	
Susceptor Ground Tube to Plate Connection	stress relaxation of joint	4	Film Stress	9	3	12	-Welded RF to top mount connector on new designs	5	240		
Susceptor Plate Warpage	heat treatment anneal at S&R Precision	3	Uniformity	6	3	9	-Specification on loading, fixtures, load size, temp ramp, duration, ramp down. Microcontrolled at S&R -Single point temp control	5	135		-Recharacterization of furnace at frequent intervals -Adopt low temp heat treatment for new susceptor designs based on consultant input

Figure 3.4: Completed FMEA Roadmap

together with several other failure mode types. After completing an FMEA, the team supplier expert, as well as the team, realized that this failure mode had a different possible root cause and may have been due to the machining of the susceptor plate around the finger hole. Once the team had identified the possible reasons for finger hole ridge formation, they were able to run a basic statistical experiment to determine whether or not a different radii on the finger hole would eliminate the nodule formation.

The third advantage of using the FMEA format is that it combined data and information from both Intel and the supplier. Although this is a subtle difference from simply supplying failure data from Intel to a supplier or having a supplier communicate progress to date, the coordination and teamwork necessary to complete an FMEA fosters better working relationships and reminds the members that they are all part of one team with a common goal of improved performance. Finally, the FMEA required sub-contractor information and served as a catalyst for several site visits by Intel to subcontractors. Since all of the data surrounding the problem was complex, the FMEA helped to organize all of the communication in one central place.

Most encouraging was the proliferation of the tool at the supplier. After they saw the important role that FMEA analysis could have in a problem solving mode, the supplier's engineering department began to apply it to other high failure rate spare parts.

3.6 Other Hints for Successful Problem Solving

There are a few lessons learned from the susceptor core team experience which can be applied to other product and process improvement team efforts. The following sections detail a few suggestions.

3.6.1 Consider suppliers as partners

The key to successful process improvement is the involvement of experts residing throughout the supply chain. This has become more important in recent years as companies have limited their engineering and manufacturing knowledge and implementation to those key areas where they feel they have a core competency and which provide a strategic advantage.

Companies will find that there are two choices. Problem solving can be delegated to the organization where the root cause most likely exists, or all affected organizations can work together on the problem. The first choice, analogous to the classic "over the wall" syndrome between manufacturing and engineering, can be short-sighted. First of all , teams have to make a judgment call early in the project as to where the root cause lies. There is a great deal of risk in taking this approach, because at the initial stages of the project the root causes are not known or verified. If the wrong organization is delegated with the responsibility to fix the problem, they may not have the necessary information or expertise.

The second approach is better since all interested parties are part of the solution identification and implementation. To get this ownership it is helpful to use a problem solving framework, like the FMEA, to organize progress and to solicit key information from all of the stakeholders. This can minimize the time it takes to do problem solving and increase the chances of team success. Once further along in the project, appropriate delegation will then be more useful, and have a higher chance of success.

3.6.2 Work around logistics to develop FMEA

For reasons just explained, the expertise to solve a problem may reside in several organizations, several companies, and in several locations. It may not be possible to always conduct meetings face-to-face. For this reason teams need to search for creative ways to overcome logistical hurdles.

The susceptor core team used some very good techniques. One was to conduct teleconferences on a routine basis instead of face-to-face meetings. This allowed the members to participate in the meeting agenda without the need to travel every week. Of course this type of meeting requires careful planning, a detailed agenda, and early publication of any overheads or supporting material, but the effort results in a better structured working session.

To complete the FMEA, and other action items, the susceptor core team simply did not require everyone involved to present at every working session. As described earlier in the chapter the lead engineers gave their input serially, with an update to the FMEA between every interview. This only required one person to travel to each FMEA participant, rather than several trips for everyone. Since personal schedules of these experts were often tight, this approach created flexibility in the project schedule and resulted in efficient completion of the FMEA.

3.6.3 Use data where available, but don't let lack of data become an obstacle

One of the most daunting parts of the FMEA formulation is the completion of the occurrence, severity and control rankings. Teams may be discouraged by the lack of data on which to base these rankings, or feel that the task is just too great, or takes too much time.

The susceptor core team did not let any of these be obstacles, but instead looked for where data did exist. The approach of using effect occurrence data in conjunction with educated guessing helped to formulate an occurrence ranking that was as justified as possible. It is important to use the 80/20 rule and realize that the relative weighting of the factors is more important than the absolute ranking value.

3.6.4 Identify a project champion to push project to closure

There is no doubt that preparing an FMEA is tedious and can often fall to the bottom of team priority lists. For this reason it is especially important to assign one team member as the FMEA champion. It is helpful if that person has had experience in preparing an FMEA, but this is not vital. The most important quality of a FMEA champion is commitment and attention to detail, as there will be many frustrating moments in FMEA preparation.

In the case of the susceptor core team I served as the FMEA champion. In this case I was an outsider to the supplier organization but could also play the role of an outsider to Intel. This worked very well since it seemed to dispel some of the group tension and allowed me to proceed with the work without an emotional stake in the outcome of the matrix. Although it is not always possible or optimum to have a champion from outside the immediate task force, in this case it seemed to work well.

3.6.5 Develop an FMEA as soon as possible in the project lifecycle

One regret of the susceptor core team is that they did not prepare an FMEA sooner. Since they waited until more that a year after the task force formation, there was some lost time gathering data and fixing root causes that were not as important as the ones identified in the FMEA. For newly formed teams it makes sense to incorporate the FMEA framework earlier in order to surface possible root causes and organize future effort.

Once the team has identified the root cause of a problem and has gathered some possible solutions, it is necessary to do analysis to decide upon the best approach. The following chapters describe the Equipment Change Impact Model, a tool designed to facilitate this decision making process.

Chapter 4

The Equipment Change Impact Model

Using a structured approach, like the Fault Tree Analysis (FTA) or Failure Modes and Effects Analysis (FMEA) described in Chapter 3, can be extremely helpful for identifying team priority and generating improvement options. Once improvement options are known, the next step in the improvement process is to reach an agreement on the best improvement strategy. Since formal tools to facilitate decision making did not exist at Intel, this step was often a source of frustration for teams. At best, the resources needed to justify a change and reach consensus for an improvement strategy were excessive.[11] In the worst case, teams were forced to make arbitrary decisions due to production pressures. In all cases investigated, the potential costs and savings of making a proposed change were unknown.

4.1 The Purpose of the Equipment Change Impact Model

The *Equipment Change Impact Model* is a Microsoft Excel based tool which was developed after observing several teams struggle with decision making. The purpose of the tool is to provide a systematic approach to problem solving by structuring quantitative and qualitative data in a way that helps teams make more informed decisions. The following sections detail the goals of this model.

4.1.1 Identify an improvement goal

The susceptor core team had a clearly defined problem statement: The lifetime of susceptors was too short and unpredictable. The final goal of the team, however, was not as easy to construct. Since neither the team, nor the OEM of the susceptor, had a clear idea of the spare part lifetime goal, it was difficult to determine if and when a proposed improvement to the susceptor design warranted testing and implementation at Intel. In addition, Intel did not have a clear idea of how much a substantial improvement in

---

[11] One team I was working with had been in place over 1 year. Several working prototypes had been identified, but no solution had been agreed upon.

performance was worth. The *Equipment Change Impact Model* is designed to help identify these goals in order to enable teams to selectively implement changes which have a substantial process impact, meeting change control goals and guidelines.

4.1.2 Provide a faster, structured approach to decision making

In order to analyze the financial impact of a proposed equipment change, many teams generated their own financial worksheet, specific to the application at hand. This customization not only requires extra resources, but also introduces variation in the decision making process across the organization, since each team has an individualized approach for analyzing data. In addition, best practices for data analysis can be lost. To decrease the amount of time necessary for analysis, the *Equipment Change Impact Model* is generic enough that it is applicable to a wide variety of projects, yet detailed enough to be useful. Since it was developed after observing several of Intel's best performing process improvement teams, it incorporates a variety of data analysis techniques in use across Intel. Thus, using the tool can decrease man-hours necessary to analyze data while providing a thorough and consistent decision making approach.

4.1.3 Determine relative importance of collected data

Teams encounter a variety of issues when faced with making a decision. For a cross functional team, there is often a dispute as to the relative importance of these categories. For instance, technology development engineers may strive to implement the latest in technology without considering the capability of a new supplier to produce equipment in production quantities. Purchasing organizations can overestimate the importance of initial cost of spares without considering the implications to process parameters. By constructing a tool which automatically determines the relative priority of these issues, contention among team members can be minimized. The *Equipment Change Impact Model* determines a relative importance of decision criteria, but allows teams to change these relations based on a given situation. This encourages consistent review of decisions throughout the organization, and requires that deviations from this approach be made consciously with group consensus.

4.1.4 Measure potential change impact

Changes of any type can require substantial resources, especially if a change is made after equipment installation. Many teams, however, overlook the resources needed to test and implement changes, or do not have a way to estimate this resource easily. As a result, teams may begin to work on a project without having enough resources identified, or worse, begin a project that requires so many resources it is not financially justified. The *Equipment Change Impact Model* provides a template for estimating the cost of change in both time and money. It also provides a quick means for determining the estimated savings of change. The combination of these two analysis helps teams to determine the financial return of a proposed change.

4.1.5 Make informed decisions consistently across organizational boundaries

Making a change to process equipment can have dramatic effects on process performance, cost, and reliability. Each function in an organization has special expertise in determining the impact of a change in all of these areas. For instance, process engineering can play a vital role in determining the process impacts of an equipment change, especially as it relates to yield and process parameter impacts. Ease of doing business with a supplier and past experience with a supplier may be best estimated by a purchasing organization. As Intel, and other companies, create cross functional teams to improve product and process performance, they increase the chance that each of these aspects will be considered when making a change. Simply forming a cross functional team may not be enough, however, to ensure that all potential aspects of a change are considered every time.

One reason for this inconsistency may be that team members do not always recognize the value they add to the decision making process, as was the case for a few teams observed at Intel. Although corporate purchasing was an ad hoc member of several key task forces they did not always attend status meetings since the perceived benefit of their time at the meetings was low. Purchasing did not know what information they needed to supply the team with, and the team did not understand the benefit they could play in the decision process. The *Equipment Change Impact Model* prompts teams for a variety of data inputs that span organizational boundaries.[12] By using the model consistently for decision making, teams can be assured that they are considering all aspects of making a change.

4.1.6 Evaluate qualitative as well as quantitative data when making a change

When looking at a process or equipment change it is easiest to focus on those aspects which are easy to quantify, such as utilization capability,[13] yield,[14] or reliability metrics. In some cases, however, non-quantifiable data can also be important. Take a second sourcing strategy of a spare part as an example. A competitive source may agree to sell each spare part at a price which is lower that the spare part currently used. After evaluating the competitive spare, the team may feel that its performance is equal to the spare currently being used and recommend switching suppliers because of lower cost. Although this example seems straightforward on the basis on quantitative data, there are other aspects of the supplier that should be evaluated. Where is the supplier located? Do they have ample capacity available to ship product on time to our delivery schedule? What is their delivery performance record? Do they have a reliability system in place to ensure that this spare part will have an equal or longer life than the spare part purchased now?

	Quantitative Data	**Qualitative Data**
Purchasing	• Equipment Capital Cost • Spare Part Unit Cost	• Ease of Doing Business with a Supplier
Process Engineering	• Process Parameters within Specification Limit • Yield Implications	• Impact to subsequent and / or previous process steps
Industrial Engineering	• Maintenance Schedule • Utilization Capability Wafer Starts/Week	• Ergonomic Risk • Safety Risk

Figure 4.1: Improvement Project Data Types and Organizational Expertise

---

[12] During testing of the *Equipment Change Impact Model* I observed that the team could not complete the model sufficiently without each team member fully engaged. Its use prompted some members to find out more information, and encouraged others to share information for the first time.

[13] Utilization Capability, or Availability, is the percentage of time a machine is available to process wafers, given the planned maintenance schedule. Actual Utilization may be lower that the capability if there are not enough wafers ready to process every time the machine becomes available.

[14] Yield is a common term used to measure the quantity of good material processed by the equipment. Line yield is the percentage of good wafers processed by the equipment. Die yield is the percentage of die which pass final electrical tests and can be sold as microprocessors. Each wafer contains several die.

Figure 4.1 shows the variety in types of data which influence decisions and the functional groups who may be best equipped to collect this data. To handle the variety of data types considered when making an equipment change, the *Equipment Change Impact Model* is divided into two parts; a qualitative decision matrix to analyze the non-quantifiable aspects of making a change and a financial impact cost model which uses numerical data to calculate actual factory costs and savings.

4.1.7 Consider the impact of variation on potential savings

Many of the inputs needed for the *Equipment Change Impact Model* can be estimated, but they vary substantially depending on environmental conditions when a change is implemented. As an example, utilization can be calculated once maintenance schedules are determined, but actual utilization can change dramatically based on factory loads and work-in-process inventory. The cost of a spare part may be estimated by a quote, but may increase in the future due to price increases, or decrease due to volume discounts. To help the user to evaluate the impact of such variations, the *Equipment Change Impact Model* allows the user to enter a range of values for many of the quantitative data types. From this information the model calculates a best and worst case scenarios for making a change.

4.2 Model Formulation

The *Equipment Change Impact Model* was developed using a concurrent engineering approach, involving the customer in the model formulation as much as possible. (See Figure 4.2) This iterative approach encouraged suggestions from customers such as process engineers, industrial engineers and finance managers. First, a prototype of the Excel 5.0 spreadsheet was shown to potential customers, using data from their own projects. This helped to foster creative suggestions as well as convince potential users of the model benefits and applicability, since they could easily see the impact of the analysis in their own working environment. Once improvement suggestions were captured, the inputs were consolidated and designed into generic enhancements applicable to as many users as possible. The modified prototype was then updated with customer data, and shown to the customer a second time. This process was repeated three times before an initial publication and proliferation of the model was attempted.

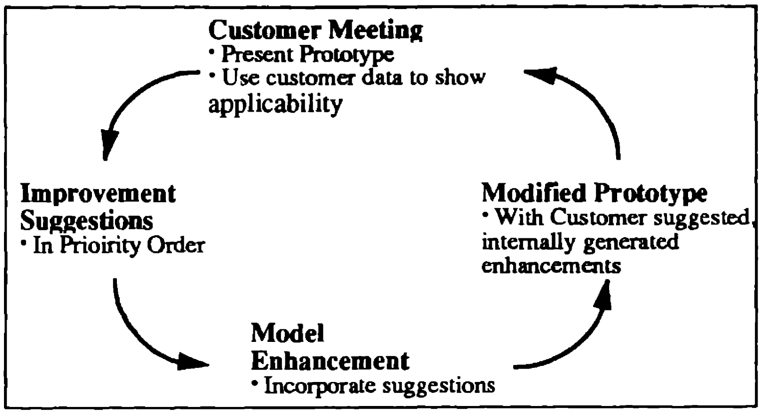


Figure 4.2: Model Formulation Process

The next four chapters explain the *Equipment Change Impact Model* in detail. Chapter 5 is an overview of the Qualitative Analysis decision matrix. Chapter 6 details the Financial Impact Worksheet, including the formulas and assumptions in the model. Chapter 7 presents several case studies, which explain how the *Equipment Change Impact Model* can be used by cost improvement teams. Finally, Chapter 8 discusses the limitations of the model and suggests areas for future research.

Chapter 5

Qualitative Analysis

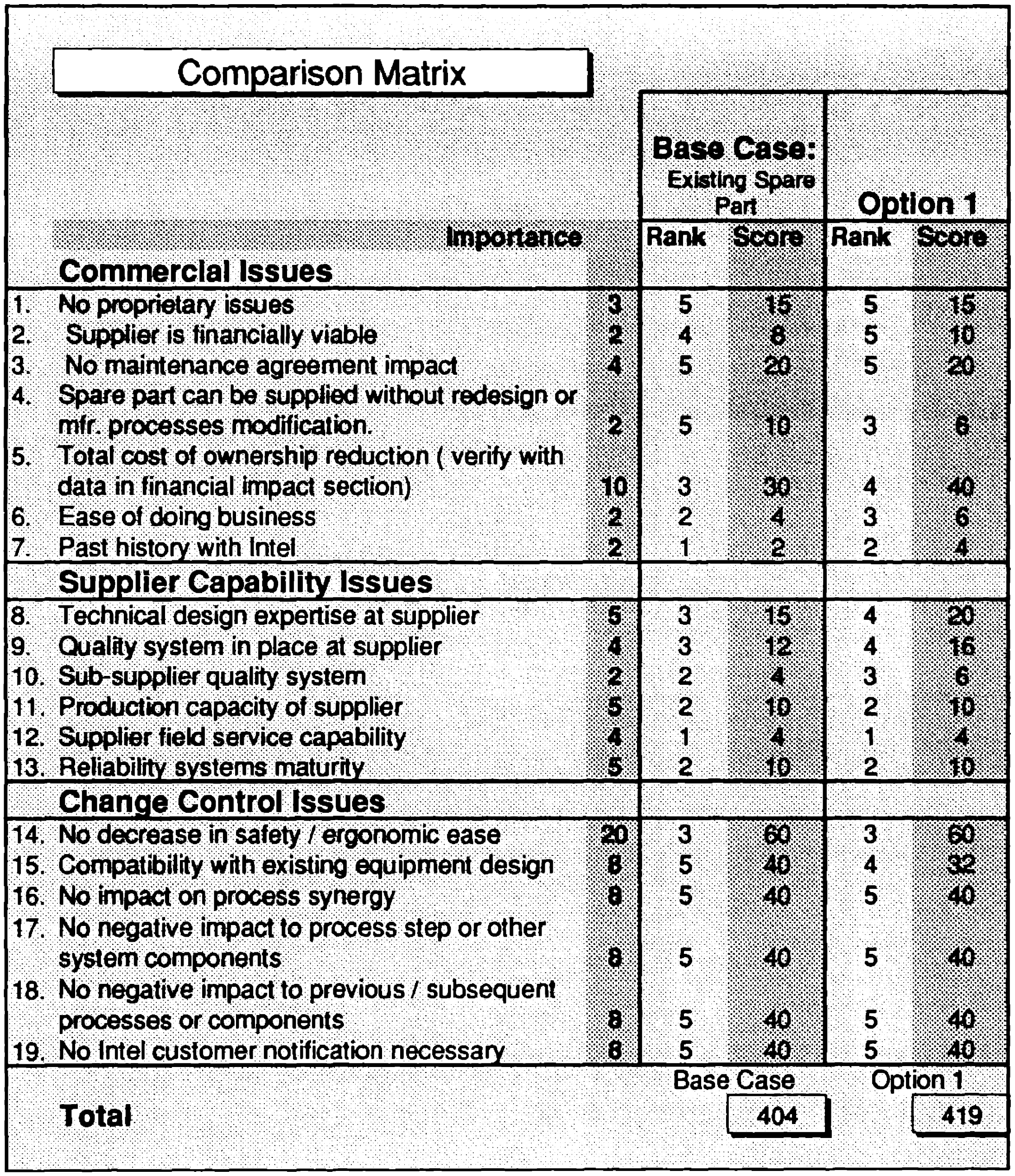
The first spreadsheet in the *Equipment Change Impact Model* is the Qualitative Analysis comparison matrix. The purpose of the Qualitative Analysis worksheet is to help teams to:

- Evaluate the improvement options compared to the existing system at the beginning project stages, or when quantitative data is unavailable.
- Consider the qualitative commercial, process, and change control impacts of making equipment changes. Teams can overlook these impacts if numerical data is the only input for decision making.

The following chapter will present an overview of the qualitative analysis spreadsheet, and present an example of how it can be used to facilitate team discussion.

5.1 Qualitative Analysis Model Overview

Figure 5.1 shows the comparison matrix used in this worksheet. The potential change issues are rows of the matrix. These issues are divided into three categories: commercial issues, supplier capability issues, and change control issues. Commercial issues are those issues which are normally addressed by a purchasing or acquisition department. Most often these issues arise when a team is considering a second sourcing or out-sourcing option. Supplier capability issues are those issues surrounding a suppliers expertise and capability to ship a quality product on time. Of the list of issues, this category is most often overlooked by an improvement team, yet it can be an early indicators of long-term success with a supplier. Change control issues are critical metrics that a team where carefully controlled change or no change is desired. Safety is an example of a change control issue. Teams making a spare part change only want to affect safety if safety levels can be carefully improved. Most teams would prefer to have no safety impact. Change control issues are often addressed by a change control board, or other review team, before a change is accepted and implemented.



Comparison Matrix

			Base Case: Existing Spare Part		Option 1	
		Importance	Rank	Score	Rank	Score
	Commercial Issues					
1.	No proprietary issues	3	5	15	5	15
2.	Supplier is financially viable	2	4	8	5	10
3.	No maintenance agreement impact	4	5	20	5	20
4.	Spare part can be supplied without redesign or mfr. processes modification.	2	5	10	3	6
5.	Total cost of ownership reduction (verify with data in financial impact section)	10	3	30	4	40
6.	Ease of doing business	2	2	4	3	6
7.	Past history with Intel	2	1	2	2	4
	Supplier Capability Issues					
8.	Technical design expertise at supplier	5	3	15	4	20
9.	Quality system in place at supplier	4	3	12	4	16
10.	Sub-supplier quality system	2	2	4	3	6
11.	Production capacity of supplier	5	2	10	2	10
12.	Supplier field service capability	4	1	4	1	4
13.	Reliability systems maturity	5	2	10	2	10
	Change Control Issues					
14.	No decrease in safety / ergonomic ease	20	3	60	3	60
15.	Compatibility with existing equipment design	8	5	40	4	32
16.	No impact on process synergy	8	5	40	5	40
17.	No negative impact to process step or other system components	8	5	40	5	40
18.	No negative impact to previous / subsequent processes or components	8	5	40	5	40
19.	No Intel customer notification necessary	8	5	40	5	40
				Base Case		Option 1
	Total			404		419

Figure 5.1: Qualitative Analysis Comparison Matrix

Since some of the issues in the qualitative analysis matrix are more important to teams than others, the matrix uses the first column, labeled *Importance*, as a relative weight of the issues. The base case columns refer to the existing equipment configuration or past equipment designs and sourcing strategies. The option 1 column provides an area to rank a potential change. Since this matrix is designed to be used during the initial stages of process improvement, several option columns are provided to compare a variety of improvement strategies. To evaluate an option as compared to the base case, a team fills in the corresponding rank columns of the matrix. Issues are ranked on a scale from 1 to 5, with 5 being the best possible design and sourcing scheme. To help teams to rank individual issues the spreadsheet uses pull down menus which describe the range of possible conditions surrounding an issue. The teams then select the description which best describes the situation they are evaluating, either the current design and sourcing strategy or a proposed changed. The possible descriptions and the corresponding ranking scores can be found in Appendix C.

Once this data is entered, the spreadsheet multiplies rank by importance for each issue, and adds the results for a total score. Teams should then compare the results to determine if an option total score is higher than the base case.

The total scoring scheme helps teams in several ways. Total scores for options which are significantly higher the base case total scores help to confirm a team's initial evaluation of a potential option. Total scores can also help teams to prioritize effort when several options exists, applying more resources to options with the higher scores. Finally, teams can compare the scoring results for a variety of issues and use the tool to develop additional hybrid solutions which address identified problematic issues.

For example, refer again to Figure 5.1. Note that Option 1 has a lower score for *Capability with existing equipment design* and *No negative impact to process step or other system components*, yet it has better scores for many of the commercial issues. Since the change control issues are heavily weighted in the matrix, the Option 1 has a total score only slightly higher than the base case. Knowing this, the team can test for *impact to process step*, and consider an alternative spare part or slight part modifications to increase the compatibility with the existing equipment design.

5.2 Qualitative Analysis Matrix Formulation and Testing

The Qualitative Analysis Matrix was designed using the iterative concurrent design approach described in Chapter 4. The initial data collection phase of the project consisted of interviews with over 12 different site buyers, process engineers, and finance managers who had been involved in identifying and implementing equipment improvements. To understand the impact changes have on the entire system, higher level management, such as the chairmen of the Change Control Board, was contacted. These individuals had experience with improvements such as second sourcing of spare parts and implementation of predicative maintenance strategies. The interview participants were asked to name issues that they considered when making a change to process equipment and the relative importance of each of these issues. The Qualitative Analysis Matrix is a compilation of this information in the form of issue descriptions and the relative importance weighting structure.

Once the descriptions and importance criteria were determined, the Qualitative Analysis Matrix was tested using the case studies of two improvement teams, one who made a second sourcing decision that was regarded as successful and one who made a second sourcing decision that was later viewed as unsuccessful and resulted in a change back to the original source. During the test each team member was asked to recall how they felt about the various issues surrounding each option before making a decision. This required that they recall their feelings before knowing if the change was successful or not. Their inputs were then reflected in the analysis matrix, and resulted in the scores shown in Fig. 5.2.

Improvement Team	**Base Case Total Score**	**Option 1 Total Score**
Successful Change Implementation	***390***	***460***
Unsuccessful Change Implementation	***420***	***450***

Figure 5.2: Qualitative Analysis Test Results

Total scores can range from 110 to 550, but most scores receive a total score between 300 and 400. Although the initial data collected from the historical case study test is inconclusive, the results do suggest that option total scores which are significantly, or greater that 50 points, higher than the base case total score are early indicators of a successful project. Regardless of the total score results, teams should complete the Financial Impact Worksheet, outlined in Chapter 6, before deciding to implement an option.

Chapter 6

Financial Impact Worksheet

The Financial Impact Worksheet, the second tool in the *Equipment Change Impact Model*, calculates the total cost impact of making a change. The purpose of the worksheet is to help teams to:

1) Evaluate the potential savings of making changes to spare part and maintenance strategies such as:
    - increasing equipment speed
    - changing maintenance schedules
    - changing monitor wafer frequency
    - lengthening replacement part life
    - lowering replacement part cost
    - buying or selling an equipment set
2) Calculate the total cost to make a change, including labor and materials used for testing.
3) Determine the payback time for a change.
4) Calculate projected, best, and worst case project savings.

The worksheet considers the total cost of process equipment which includes the costs of maintainability, reliability, utilization, and yield. These costs, when aggregated over the equipment life are often greater than the initial cost of the equipment, shifting the emphasis of many purchasing departments from purchase price to equipment maintenance and support costs. Since Intel uses total cost for buying new equipment and considering new equipment upgrades, incorporating total cost in the Financial Impact Worksheet eased proliferation challenges.

6.1 The Total Cost of Ownership Algorithm

The purchasing department of Intel, as well as many equipment suppliers, routinely use a model developed by SEMATECH called the Total Cost of Ownership when making capital acquisition decisions. The basic cost of ownership algorithm[15] used in the SEMATECH model can be described by:

$$C_W = \frac{C_F + C_V + C_Y}{TPT \times U} \tag{6.1}$$

where:
C_W = Cost per wafer ($/wafer)
C_F = Fixed cost
C_V = Variable cost
C_Y = Cost due to yield loss
TPT = Throughput
U = Utilization

This analysis provides an easy way to compare different process technologies by dividing the costs necessary to produce wafers by the total number of wafers produced. As a result, this simple approach measures the cost of quality and equipment throughput for a variety of applications. For instance, a new technology that is more expensive but has fewer wafer losses and higher throughput as compared with older technologies may actually reduce the cost per wafer. This information can then be used to formulate technology strategies for new manufacturing facilities, or suggest areas to upgrade in existing facilities.

The Financial Impact Worksheet algorithm differs from the cost of ownership algorithm shown in equation 6.1 in two important ways:

1. The Financial Impact Worksheet does not calculate an absolute cost per wafer for an equipment set: It calculates savings or costs per wafer by considering only the changes in total cost after implementing an improvement. This simplifies the model substantially by requiring fixed cost information, such as purchase or installation costs for equipment, only when an equipment set is added or removed as a result of a change.

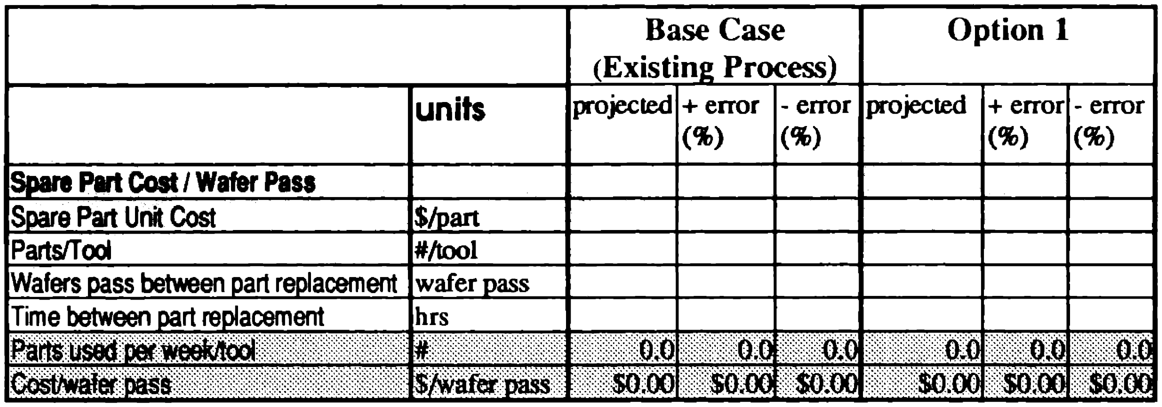
---

[15] Adapted from Dance, Daren. "Applications of Cost-of-ownership." Semiconductor International Sept. 1994: 6-7

2. Many cost of ownership models currently require users to provide utilization estimations. While some users have formulated algorithms and auxiliary models to estimate utilization, some users rely on supplier estimation or past performance for this value. Since the cost of ownership is highly sensitive to changes in utilization, this reliance can be short sighted, and result in significant analysis errors. For this reason, the Financial Impact Worksheet calculates utilization capability based on the maintenance schedule and compares it to planned work-in-process to calculate an actual utilization. The model then uses this information to calculate savings per wafer or costs per wafer. When capacity is constrained, any increase in utilization capability will result in an increased savings per wafer to reflect the additional throughput capacity. Increased capacity will not increase savings per wafer if no more product is available to process, as in the case of non-bottleneck equipment.

6.2 Financial Impact Worksheet Overview

Figure 6.1 shows a portion of the Financial Impact Worksheet. The Base Case columns provide user input cells to enter existing process data and the Option columns provide user input cells to enter estimated data for a change. Shaded cells represent protected or internally calculated cells. White cells are available for user input, but with the exception of a few mandatory input cells can be left blank if they are not applicable to a given situation. The projected column for both the Base Case and Option 1 is used for the average or expected value of a data input. The "+ error" and "- error" columns allow a user to enter high and low % data where process uncertainty exists. For example, if the unit cost of a spare could be as much as 5% higher than the projected value, the user should enter 5% in the "+ error" column. Similarly the "- error" column can be used if a data input could be lower than the projected value. The Financial Impact Worksheet uses the error column information to calculate best case and worst case savings in order to analyze the effect of process variation on expected return. For instance, if the unit cost of a newly designed replacement part has an expected cost of $10 and the current cost is $12, the expected savings is $2. But if volume discounts from a supplier occasionally reduce the cost to $9 for some purchases, the savings increases to $3 in the best case.



		Base Case (Existing Process)			Option 1		
	units	projected	+ error (%)	- error (%)	projected	+ error (%)	- error (%)
Spare Part Cost / Wafer Pass							
Spare Part Unit Cost	$/part						
Parts/Tool	#/tool						
Wafers pass between part replacement	wafer pass						
Time between part replacement	hrs						
Parts used per week/tool	#	0.0	0.0	0.0	0.0	0.0	0.0
Cost/wafer pass	$/wafer pass	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00

Figure 6.1: Financial Impact Worksheet: Spare Part Cost / Wafer Pass

reduce the cost to $9 for some purchases, the savings increases to $3 in the best case. Similarly, if a price increase could raise the price to $11, the savings decreases to $1 in the worst case. By providing results for the projected, best, and worst case scenario, the user is more informed of the impact of data variability and can be better equipped to minimize possible risk.

The following sections of this chapter describe the user input cells, the calculated result cells, and the summary information of the Financial Impact Worksheet in detail.

6.3 Financial Impact Worksheet User Inputs

The user input sections are divided into the following categories:

- Spare Part Cost / Wafer
- Process Equipment Information
- Scheduled Downtime
- Unscheduled Downtime
- Capacity Planning Information
- Specific Process Line Yield Costs
- Investment / Implementation Costs
- Cost of Change
- Overhead Costs

6.3.1 Spare Part Cost per Wafer

The Spare Part Cost per Wafer section, shown in Figure 6.1, is specifically designed to analyze the cost per wafer of one spare part for a given equipment set. The model calculates the cost per wafer based on the unit cost of the spare and the replacement schedule specified in this section. This is the only section of the model where a spare part can be analyzed independent of a routine maintenance step. This was specifically designed for increased modeling flexibility and allows the user to evaluate situations where a spare part is not replaced during every scheduled PM. For instance, the susceptor described in Chapter 3 was replaced at every other PM. To use the Financial Impact Worksheet correctly the user would enter the spare part replacement information in the Spare Part Cost per Wafer section. Since the Spare Part Cost per Wafer section does not include an input cell to reflect the average time it takes to replace the spare, the user must also enter the average downtime information in the Scheduled Downtime section. Specific examples on how to use this section can be found in Chapter 7.

6.3.2 Process Equipment Information

This section, shown in Figure 6.2, provides the run rate, or wafer pass per hour capability, of the process equipment being analyzed.

		Base Case (Existing Process)			**Option 1**		
	units	projected	+ error (%)	- error (%)	projected	+ error (%)	- error (%)
Process Equipment Data							
Wafer Pass per Hour	wafer pass/hr						

Figure 6.2: Financial Impact Worksheet: Process Equipment Data

The model uses this input along with the scheduled and unscheduled downtime information to calculate the utilization capability. The wafer pass per hour input is one of the few cells which must be entered for the model to calculate financial returns correctly; it is identified by a red perimeter. (shown as a bold outline in Figure 6.2)

6.3.3 Scheduled Downtime

Maintenance procedures may be scheduled, in the case of preventative maintenance (PM), or unscheduled and performed after a machine breakdown. The model separates these to facilitate data entry.

There are two ways to schedule downtime: on a time basis or a wafer pass basis. Time based PMs are performed after a specified time has elapsed, regardless of how many wafers are processed through the system. Wafer based cycles use the amount of material processed by the equipment to determine PM timing. Wafer based maintenance schedules are best for spare and consumable replacement, which depend on the amount of wafers processed. Scheduling based on wafers processed also allows for an increase in PM frequency as the production rate in new factories increases; likewise it allows for a decrease in PM frequency during periods of low production.

Time based PM's are useful for the maintenance of parts which wear as a function of time only, and are independent of the amount of wafers processed. Many factories combine a wafer based strategy for frequent, routine PM's with a time based strategy, often scheduled as semi-annual and annual intensive PM's. The model allows for any combination of these approaches by using the appropriate input categories listed in Figure 6.3.

Wafer Based Downtime Categories	Time Based Downtime Categories
Minor PM	Quarterly PM
Major PM	Semi Annual PM
Super PM	Annual PM
	Other PM
Monitor Steps	Weekly Monitor Step

Figure 6.3: Scheduled Preventative Maintenance Downtime Categories

In the wafer based category, minor PM's are those which are done more frequently, or after a fewer amount of wafer passes, but require less time and material cost. Major PM's are more significant, often requiring additional time and material. Super PM's are major teardowns, which are often very labor intensive, and require the replacement of many spare parts. The algorithms are the same for each of these categories, which allows flexibility for the user to enter specific data in these cells which may not fit the category title.

Similarly, the model allows for time based PM strategies, and provides 4 input categories. The titles of these categories, quarterly vs. annual, suggest a frequency of occurrence although the algorithms for each input category is the same. The *other downtime* category can be used for yearly shutdowns, vacation time or other factory downtime not represented by the maintenance/monitor categories.

Monitor steps are routine process checks to monitor process characteristics[16] and provide data for statistical process control. Often the monitor steps are not done on production wafers since the post processing tests can be destructive.[17] Since monitor steps use time which would otherwise be used to process production wafers, they are considered a form of scheduled downtime in this model. The model provides for wafer based and time based monitor steps.

The model asks for the replacement part cost for each of the scheduled maintenance steps. Often this will include spare parts, consumables, and some cleaning materials, like clean room wipes, which are used during the maintenance steps. The model also prompts for the number of monitor wafers used during each monitor step. This information is used by the model to calculate the material cost of maintenance, which will be explained later in this chapter.

Each section also includes an input cell for the number of technicians required for each maintenance step. The model assumes that only one technician is needed to run a monitor step. This information is used by the model to calculate the labor costs of maintenance, which will be further explained later in this chapter.

---

[16] An example of a process characteristic in the thin films area is film uniformity and surface resistivity.

[17] The wafers used for the monitor steps are routinely called monitor wafers. These are often less expensive than production wafers, and may not have received all of the processing steps that the routine production wafers have.

6.3.4 Unscheduled Downtime

Unscheduled downtime is reactive maintenance that occurs when an equipment set fails unexpectedly for some reason. Unscheduled downtime can be predicted with historical data, either as a mean and standard deviation of time between failures, or as a mean and standard deviation of material processed between failures. Most factories use time between failures (Mean Time Between Failures, or MTBF) or wafers processed between failures (Mean Wafers Between Failures, or MWBF) when describing failure occurrences. Often the unit of measurement, either wafer based or time based, is the same as the scheduled downtime unit most frequently used.

		Base Case (Existing Process)			Option 1		
	units	projected	+ error (%)	- error (%)	projected	+ error (%)	- error (%)
Unscheduled Downtime							
Mean wafers between failure (MWBF)	wafer pass						
Mean time between failures (MTBF)	week						
Mean time to repair (MTTR)	hrs						
Mean materials to repair failure	$/incident						
# Technicians needed	#						
Materials needed to repair failures	**$/wafer pass**	**$0.00**	**$0.00**	**$0.00**	**$0.00**	**$0.00**	**$0.00**
Unscheduled labor hrs/week	**hrs/week**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**

Figure 6.4: Financial Impact Worksheet: Unscheduled Downtime Section

The unscheduled downtime section, shown in Figure 6.4, will allow either MTBF or MWBF to predict unscheduled downtime, but not both.[18] The "+ error" and "- error" columns can be used to model the standard deviation.

As in the case of scheduled maintenance, the section also includes input cells to reflect the materials and labor required for an unscheduled downtime occurrence. Since an unscheduled maintenance incident is unplanned by definition, it will be impossible to estimate this exactly. The user should enter the average material costs and labor

---

[18] If the user tries to enter data in both MTBF and MWBF rows an error message will appear, instructing the user to delete the data in one of these rows.

requirements, based on historical data and use the "+ error" and "- error" columns to account for the variation of occurrences.

6.3.5 Capacity Planning Information

The capacity planning section allows the user to identify the wafers/week/tool that the equipment must be able to process in order to avoid creating an isolated bottleneck in the factory. While the downtime information is used to calculated the capability of the equipment without regard for the factory needs, the capacity planning section helps to establish the actual production goal for the equipment.

		Base Case (Existing Process)			**Option 1**		
	units	projected	+ error (%)	- error (%)	projected	+ error (%)	- error (%)
Capacity Planning Information							
Wafer starts/week	# /week						
# of layers(wafer passes)/wafer	wafer pass/wafer						
# of equipment sets in factory	#						
Total Floor Space Needed	Square Feet						
Capital Cost/Equipment	$/equipment						

Figure 6.5: Financial Impact Worksheet: Capacity Planning Section

To calculate the wafers/week/tool that the equipment must be able to process, the model needs to know the number of wafer starts in the factory (or the total number of wafers/week that the upstream equipment can process/week), the number of tools, or equipment sets, planned for the factory, and the number of layers per wafer that the equipment must process. For instance if there are 1000 wafer starts per week, 10 diffusion layers in the current design, and 10 diffusion furnaces planned for the factory, each furnace must be able to process 1000 wafer starts/week/tool in order to handle all of the work-in-process.

In some cases the wafer starts/week/tool capability may be much greater than the wafer starts/week/tool needed in order to process the WIP. In this case, it may be possible to eliminate a tool, or equipment set. The model allows the user to input the floor space occupied by each tool or equipment set, and the cost of each tool or equipment set in order to calculate the savings when a reduction in required tools is possible. For more information on how this section can be used to aid in capacity planning see Chapter 7. In other cases, this analysis may highlight a situation where there is not enough capacity to keep up with production needs. Depending on the situation, this may prompt the user to install an additional equipment set, or search for ways to increase the utilization capability.

6.3.6 Specific Process Line Yield Costs

Line Yield is defined as the percentage of wafers that are successfully processed by an equipment set, and line yield loss is the percentage of wafers that must be scrapped due to breakage, misprocessing, etc. This section of the model is designed to account for the line yield ramifications of equipment changes. The model asks for the average percentage (%) of wafers that are lost due to line yield at the process step being analyzed, which is a metric often measured in the factory. This information is then multiplied by the actual wafers processed in order to calculate the total number of wafers lost at an analyzed process step per week.

When a change is made to a spare part, or to maintenance strategies, the line yield can be directly affected. The purpose of this section is to help estimate potential savings as a result of changes that improve line yield. Two types of cost factors are used to calculate this savings. One is the wafer cumulative cost at the process step being analyzed. This is the cost of the wafer itself plus any labor or materials which have been applied to the wafer before the process step is performed. Often this cost must be an average of the cost of all wafers processed at the step, especially if more that one wafer recipe is used in the same plant, or if the equipment is used to process several layers. The model always calculates savings by comparing the line yield loss before and after a change and multiplying by the wafer cumulative cost.

Another way to analyze cost is to look at the opportunity cost of a lost wafer, or the revenue that Intel could have received if the wafer was produced. On a non-bottleneck station this metric is very difficult to estimate, since all wafers produced at a non-bottleneck step may not produce a revenue generating product. On a bottleneck station in a capacity constrained factory, however, line yield losses can be directly translated into revenue dollars lost since Intel is in the enviable position to sell everything that it makes. The model will only calculate revenue differences if the user specifies that the equipment being analyzed is a factory constraint (See Financial Impact Worksheet: Results, section 6.4 of this chapter, for more details).

6.3.7 Investment / Implementation Costs

Investment or Implementation Costs are one time payments made at the beginning of a project to cover implementation costs or fund development work. Examples of these costs would be one time R&D funding to a supplier for a given project, costs of implementing a particular change, or any resources needed to make a change not covered under Cost of Change section (see below).

6.3.8 Cost of Change

The cost of change section helps the user to approximate the amount resources necessary to make a change within the Change Control Board structure at Intel. Since Intel follows a very regimented change control policy, every proposed change must follow a sequential process of Preliminary White Paper preparation and Final White Paper preparation. The Preliminary White Paper contains the results of any feasibility tests, justification for making a change, and the proposed test and implementation plans. Often the preparation for a Preliminary White Paper is performed by a subteam of process engineers with the assistance of lab personnel and technicians. The test plan submitted in conjunction with the Preliminary White Paper often includes a series of tests performed on monitor wafers, as well as production wafers, in order to fully characterize the process after the change and eliminate potential risk. This plan must be submitted through the Process Change

Control Board (PCCB) and other cross functional review boards that are affected by the change, such as the Yield, or Reliability board[19].

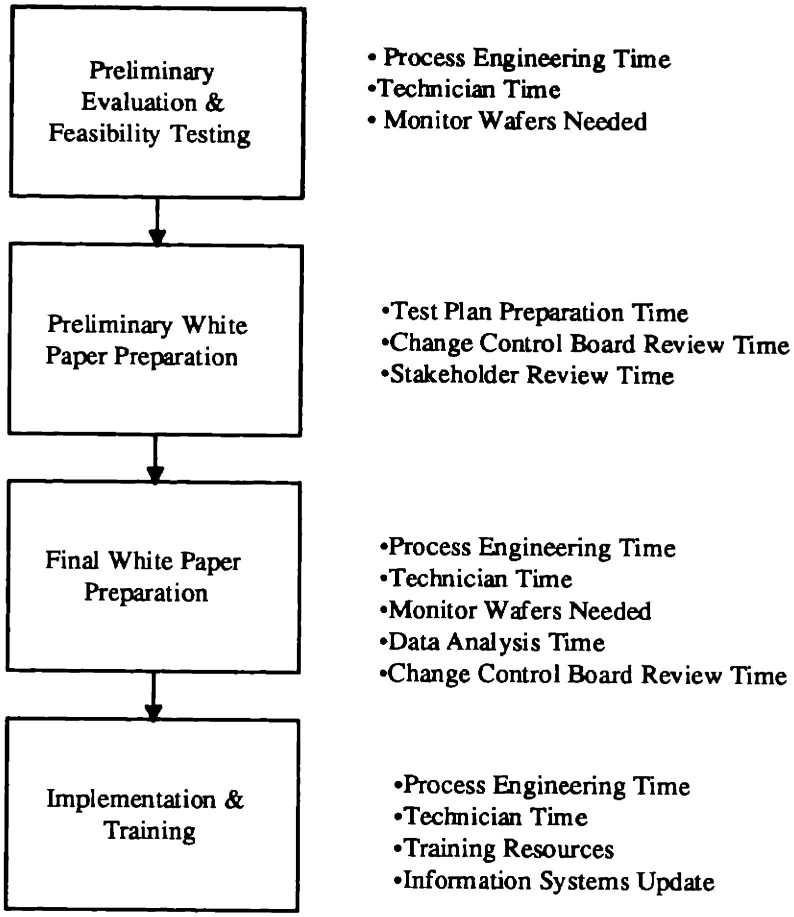


Figure 6.6: Intel Change Control Process

The Final White paper includes the results of the testing, and must be reviewed by the same group of teams before implementation can proceed. Once approved, implementation resources as well as training resources may be required.

---

[19] The Yield and Reliability boards, or JETs (Joint Engineering Teams), are cross site teams aimed at creating cross site process synergy. Changes which can affect yield or reliability must be approved by these teams before they are accepted for implementation.

The input cells of the cost of change section are arranged according to the stages of the change control process used at Intel. Figure 6.6 shows the generic change control process flow and examples of the data inputs prompted at each stage. The spreadsheet prompts the user for the total number of hours necessary to complete each step as well as the cycle time necessary to complete the change process. This information is directly used in the summary section to calculate the Net Present Value of making a change as well as the payback period needed to recover the investment of making a change.

6.3.9 Overhead Costs

Overhead costs are the resources needed from support organizations, like purchasing, to make a change and support the change on an ongoing basis. One example is the resources necessary to complete a SSQA[20] evaluation of a possible source. Another example is the site buyers which are necessary to support a given commodity area. In some cases, especially in the case of second sourcing, the support resources necessary to manage the larger supplier base increases. This section is designed to reflect these additional needs.

6.4 Financial Impact Worksheet Results

Based on the inputs provided by the user, the Financial Impact Model provides several calculations. The calculations are write protected and highlighted in yellow on the spreadsheet. Except where noted these calculations are done individually for the Base Case and Option 1 and then compared to determine if the proposed change results in a savings or in extra cost.

---

[20] The SSQA evaluation (SEMATECH Supplier Quality Assessment) was developed in 1994 in conjunction with SEMATECH partner firms to create a systematic methodology for evaluating semiconductor equipment suppliers. The assessment, which is designed to be performed by a cross-company team of trained assessors, is used to rate suppliers on their management commitment, systematic approach, implementation, and key results of over 50 attributes of a world class supplier. The results are recorded in a centralized SEMATECH database and available to all partner firms.

6.4.1 Capability Calculations

The Capability Calculations are the most important in the Financial Impact Worksheet, as they determine the cost/wafer of every other spreadsheet section. The following subsections detail each calculation contained in this section.

6.4.1.1 Wafer pass/week/tool capability

Wafer pass/week/tool capability is the total number of wafers that each machine can process every week, given the amount of downtime specified in the scheduled and unscheduled downtime sections of the model. To calculate capability, the spreadsheet assumes that the total factory time is divided into Utilization Capability, Scheduled Downtime, and Unscheduled Downtime, as shown in Figure 6.7.

<table>
<tr><th colspan="10">Total Time</th></tr>
<tr><th colspan="2">Utilization Capability</th><th colspan="7">Scheduled Downtime</th><th>Unscheduled Downtime</th></tr>
<tr><td rowspan="3">Idle Time</td><td rowspan="3">Utilization</td><td colspan="5">Time Based Downtime</td><td colspan="2">Wafer Based Scheduled Downtime</td><td rowspan="3">* Note: This may be scheduled or unscheduled, depending on how failure data is collected and monitored</td></tr>
<tr><td colspan="4">Time Based PMs</td><td rowspan="2">Time Based Monitors</td><td rowspan="2">Wafer Based PM</td><td rowspan="2">Wafer Based Monitors</td></tr>
<tr><td>Quarterly</td><td>Semi-Annual</td><td>Annual</td><td>Other Downtime</td></tr>
</table>

Figure 6.7: Financial Impact Worksheet Total Time Assumptions

In this diagram Total Time is the available time in the factory. For a three shift operation, 7 days/week, Total Time = 128 hrs/week.

Wafer Pass/Week Capability can be calculated by multiplying the Run Rate, or throughput rate entered in the Process Equipment Information section by the total time available to run production material, or:

$$\frac{WaferPass}{Week} = RunRate\left(\frac{TotalTime}{Week} - \frac{ScheduledDowntime}{Week} - \frac{UnscheduledDowntime}{Week}\right) \quad (6.2)$$

To calculate Scheduled Downtime/Week the model must account for time based and wafer based schedules which leads to the equation:

$$\frac{ScheduledDowntime}{Week} = WaferBasedDowntime + TimeBasedDowntime \tag{6.3}$$

where

$$WaferBasedDowntime = \left[\frac{WaferPass}{Week}\left(\frac{PMHrs}{WaferPassBetweenPM} + \frac{MonitorTime}{WafersBetweenMonitor}\right)\right] \tag{6.4}$$

and

$$TimeBasedDowntime =$$

$$WeeklyMonitorTime + \frac{AnnualPMTime}{52} + \frac{SemiAnnualPMTime}{26} + \frac{QuarterlyPMTime}{13} + Other \tag{6.5}$$

Unscheduled Downtime can also be time-based or wafer-based, depending on the method of data collection. If a wafer-based approach is used, the Mean Wafers Between Failure, or MWBF, must be multiplied by the Wafer Pass/Week to convert wafers to a time-based metric, as in equation 6.6. If Mean Time Between Failure, MTBF, is used, this conversion is unnecessary.

$$\frac{UnscheduledDowntime}{Week} = \frac{WaferPass}{Week}\left(\frac{MeanTimeTo\,\mathrm{Re}\,pair(MTTR)}{MeanWaferBetweenFailure(MWBF)}\right) \tag{6.6}$$

or

$$\frac{UnscheduledDowntime}{Week} = \frac{MeanTimeTo\,\mathrm{Re}\,pair(MTTR)}{MeanTimeBetweenFailure(MTBF)} \tag{6.7}$$

The model assumes that either MTBF or MWBF is used as a factory metric and allows either one to be used in the Wafer Pass/Week Capability calculation. Thus, combining Scheduled and Unscheduled Downtime in the Wafer Pass/Week Capability Equation results in the following equation:

$$\frac{WaferPass}{Week} = RunRate\left[\frac{TotalTime}{Week} - \frac{WaferPass}{Week}\left(\frac{PMHrs}{WaferPassBetweenPM} + \frac{MonitorTime}{WafersBetweenMonitor} + \frac{MTTR}{MWBF}\right) - \left(TimeBasedDowntime + \frac{MTTR}{MTBF}\right)\right] \quad (6.8)$$

Removing Wafer Pass/Week from the right hand side of equation 6.8 simplifies the equation to:

$$\frac{WaferPass}{Week}\left[1 + RunRate\left(\frac{PMHrs}{WaferPassBetweenPM} + \frac{MonitorTime}{WafersBetweenMonitor} + \frac{MTTR}{MTBF}\right)\right] = RunRate\left[\frac{TotalTime}{Week} - \left(TimeBasedDowntime + \frac{MTTR}{MTBF}\right)\right] \quad (6.9)$$

or

$$\frac{WaferPass}{Week} = \frac{RunRate\left[\frac{TotalTime}{Week} - \left(TimeBasedDowntime + \frac{MTTR}{MTBF}\right)\right]}{\left[1 + RunRate\left(\frac{PMHrs}{WaferPassBetweenPM} + \frac{MonitorTime}{WafersBetweenMonitor} + \frac{MTTR}{MWBF}\right)\right]} \quad (6.10)$$

6.4.1.2 Wafer pass/week/tool needed to process WIP

The wafer pass/week/tool needed to process WIP (work in process) is calculated from the Capacity Planning Information input section and is the amount of wafers the equipment must process each week to avoid a factory bottleneck. The model uses the following equation:

$$\frac{WaferPassNeededToProcessWIP}{week/tool} = \frac{\left(\frac{WaferStarts}{Week}\right)\left(\frac{\#ofWaferPasses}{Wafer}\right)}{\#ToolsInFactory} \quad (6.11)$$

To arrive at this number, the team must know the wafer starts per week that are planned for the factory. Since each wafer may require more than one pass, or processing step, per piece of equipment, the wafer pass capability may need to be higher than the wafer starts per week in the factory.[21] By the same logic, if more than one tool is available in the factory to run a given step, the wafer pass capability per tool will be less.

6.4.1.3 Utilization Capability

Utilization Capability is the theoretical percentage of time that the equipment set can process production material based on the specified scheduled and unscheduled downtime. To calculate this, the model uses the scheduled and unscheduled downtime calculated in equations 6.3 and 6.7, and the following equations to find the Utilization Capability percentage:

$$UtilizationCapability = \frac{\left(\frac{TotalTime}{Week} - \frac{ScheduledDowntime}{Week} - \frac{UnscheduledDowntime}{Week}\right)}{\frac{TotalTime}{Week}} \quad (6.12)$$

or

$$UtilizationCapability = \left[1 - \frac{\frac{ScheduledDowntime}{Week}}{\frac{TotalTime}{Week}} - \frac{\frac{UnscheduledDowntime}{Week}}{\frac{TotalTime}{Week}}\right] \quad (6.13)$$

6.4.1.4 Actual Utilization

Actual Utilization is the percentage of total time that the equipment set actually processes wafers. Actual Utilization assumes that the equipment will process whatever is smaller, either wafer pass/week/tool capability or wafer pass/week/tool needed to process the upstream WIP.

For instance, if the equipment set is a factory bottleneck, there will be more WIP in the system than the equipment can process, and actual wafers processed will be limited to the capability of the equipment set. In this case, actual utilization will be calculated using wafer pass/week capability. If the equipment is not a bottleneck, the actual wafers

---

[21] There are other reasons why the wafer pass capability must be higher than the wafer starts per week. One is that wafer can be lost due to line yield loss. In addition, the factory may plan for some process areas to have extra capacity in order to manage production flow easier.

processed will equal the amount of wafers in the pipeline ready to be processed. In this case actual utilization will be calculated using Wafer Pass needed to Run WIP.

The model uses the following equation to calculate Actual Utilization which compares the number of wafers actually processed with the number of wafers that the machine could process given no downtime:

$$ActualUtilization = \frac{MIN\left(\frac{WaferPassNeededToProcessWIP}{Week}, \frac{WaferPass}{Week}\right)}{\frac{RunRate}{TotalTime/Week}} \qquad (6.14)$$

6.4.1.5 U/A

U/A (Utilization/ Utilization Capability or Availability) is a calculation which helps factory planners and process engineers assess how much of utilization capability is being used for production and how close equipment is to becoming a potential bottleneck. For non-bottleneck stations, many teams strive for U/A values of approximately 0.80 since a higher value indicates a potential bottleneck. Lower values indicate that extra capacity is available, and a machine could potentially be eliminated.

To calculate U/A, the model uses the equation 6.15:

$$\frac{ActualUtilization}{UtilizationCapability} \qquad (6.15)$$

6.4.1.6 Actual Wafer Out/Week

All of the calculations so far have been based on the amount of wafer passes, not the total amount of wafers produced. The Actual Wafer Out/Week calculation is used to present a realistic number of wafers that will be processed through the system as well as provide an input for the summary section, described in section 6.6 of this chapter.

To calculate Actual Wafers Out/ Week the model uses the equation:

$$\frac{ActualWafersOut}{Week} = \frac{MIN\left[\frac{WaferPassNeededToProcessWIP}{Week}, \frac{WaferPass}{Week}\right]}{\frac{WaferPass}{Wafer}} \tag{6.16}$$

which accounts for situations where more than one pass through the equipment is required per wafer.[22]

6.4.2 Itemized Cost Information

Each scheduled downtime and unscheduled downtime section provides an itemized cost summary which calculates the material costs/wafer pass and the labor hours/week necessary to support the downtime specified in the Base Case and Option 1.

		Base Case (Existing Process)			**Option 1**		
	units	projected	+ error (%)	- error (%)	projected	+ error (%)	- error (%)
Scheduled Downtime							
Wafer Based Cycles							
Minor PM							
Mean wafers between minor PM	wafer pass						
Time to perform minor PM	hrs/PM						
Additional Material Cost	$/PM						
# Technicians needed	#						
Wafer based minor PM frequency	**PM/wk**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
PM Additional Material cost/wafer pass	**$/wafer pass**	**$0.00**	**$0.00**	**$0.00**	**$0.00**	**$0.00**	**$0.00**
Minor PM technician time per week	**hrs/week**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**

Figure 6.8: Itemized Cost Results Example

The material cost/wafer pass is determined by dividing the total amount of materials necessary to perform the maintenance step every week by the Actual Wafer Pass/Week/Tool processed by the equipment set.

---

[22] Since there are often more than once layer of a given material on a wafer, most wafers will see many process stations more than once. Lithography is one area which processes wafers several times during wafer fabrication.

To calculate labor hours/week, the model multiplies the number of technicians specified in each user input section by the number of hours the equipment is down for maintenance each week for a given maintenance step. This calculation makes the assumption that the technicians must be present for the entire time that the equipment is down, which may not be the case for some machines that are equipped with self maintenance features. If a technician is not needed throughout the specified maintenance step, the user should enter 0 or some fraction of technicians in the *# of Technicians needed to perform PM* cells.

6.4.3 Line Yield Cost

Changes made to spare parts or maintenance practices can also have an impact on equipment line yield. The results presented in the Line Yield Cost section estimate the savings which results from line yield improvements, or the extra costs associated with a change that decreases line yield. To calculate line yield cost the model uses the equation:

$$LineYieldLoss = \%ofWafersLost \times \frac{ActualWafersOut}{Week} \times \frac{CummulativeCost}{Wafer} \quad (6.17)$$

This calculation allows the user to evaluate the impact of reducing (or increasing) the percentage of wafers lost. Since the cumulative cost/wafer increases with each step in the process, line yield improvements at steps just before shipping have a greater impact on total cost than the first steps in wafer fabrication. As a result, using this type of analysis exclusively can lead to a factory emphasis on improvement projects which target equipment used at the end of the wafer processing cycle. This may or may not be appropriate, especially if there is one equipment set which is the factory bottleneck. For this reason, line yield improvements which impact a bottleneck station are also included in the Revenue Opportunity Cost section, explained below.

6.4.4 Revenue Opportunity Cost

When an equipment set limits the output of a factory, either because of wafer pass capability or because there are too few equipment sets, it is a factory bottleneck. If more wafers can be processed by this station, more product per week can be made. In a capacity constrained factory, such as Intel, an increase in wafers produced directly affects the amount of revenue generated.

There are two ways to increase the number of wafers produced per week. One way is to increase the throughput of the equipment by decreasing downtime, or improving equipment speed. In the Financial Impact Worksheet this increase is reflected in the actual wafer pass/week number. The second way to increase the number of wafers produced per week is to improve line yield, which directly increases the number of wafers available to sell. The Financial Impact Worksheet takes the line yield improvement number from the line yield cost section of the model.

Before using this section of the spreadsheet, the user should identify whether or not the equipment set being analyzed is indeed a factory bottleneck. If so, the user should enter the expected revenue/wafer as an input and the model will calculate the additional revenue which will be generated from making the proposed change using the following 2 formulas.

$$\begin{gathered} Additional\,\mathrm{Re}\,venueFromThroughput\,\mathrm{Im}\,provements = \\ \left(\frac{ActualWafersOut_{Options}}{Week} - \frac{ActualWaferOut_{BaseCase}}{Week} \right) X \,\frac{\mathrm{Re}\,venue}{Wafer} \end{gathered} \tag{6.18}$$

Similarly,

$$\begin{gathered} Additional\,\mathrm{Re}\,venueFromLineYield\,\mathrm{Im}\,provements = \\ \left(LineYield_{Option} - LineYield_{BaseCase} \right) X \,\frac{\mathrm{Re}\,venue}{Wafer} \end{gathered} \tag{6.19}$$

6.4.5 Cost of Change

As described earlier in this chapter, a formalized change control process can require a large number of resources, both in engineering time and in materials needed for adequate testing and pilot runs. Since this cost is perceived to be high, it can have two affects on team progress. The first effect is that teams may prematurely abandon an idea before testing its feasibility. For this reason, worthwhile projects may be overlooked. On the other hand, teams may forge ahead on a project, applying valuable time and resources, when the resulting improvement is not substantial. To address this issue the Financial Impact Worksheet includes a cost of change section which calculates:

1. The resources necessary to make a change. The resources include both the labor costs necessary to make the change as well as any material costs to make a change. The labor cost is calculated from the total number of technician and process engineer hours entered in the input section multiplied by an hourly rate which includes salary and benefits. The material costs are calculated based on the monitor and process wafers which must be used during the testing phase of the change.
2. The cycle time to complete a change, from concept feasibility studies to implementation. This cycle time is simply the sum of the time that the user specifies for each phase of the equipment stage: Concept Feasibility, Preliminary White Paper, Final White Paper, and Final Implementation and Training.

As discussed earlier in this chapter, the user inputs the time and resource estimates necessary to complete the proposed change. The model then calculates the cost of the labor and materials used.

The cost of change section also allows the user to enter the number of process wafers that will be at risk if the proposed change is tested and implemented. This section was added as a result of talking with some improvement teams who could only test proposed changes on production material, or were forced to implement a change in production quickly due to obsolescence in spare material or other crisis situations. In this case, implementing a change could have damaged production material, causing additional scrap and lost revenue. The spreadsheet captures this risk by reporting inputs entered in this section to the summary statistics separately.

6.4.6 Cash Flow Columns

Cash flow columns are based on the individual cost sections just described and are available for the projected return, the best case and the worst case scenario. This section of the chapter will explain the basis for the projected return columns, and the best and worst case scenario columns will be described in detail in the Sensitivity Analysis section, later in this chapter.

In order to calculate the savings for a given scenario the spreadsheet compares the base case costs with the option 1 costs and determines a resulting savings or cost of making the change. These savings and costs are represented as positive or negative cash flows respectively. The spreadsheet separates the cash flows into one of the following types of flows: Savings (or Cost) per Wafer Pass, Savings (or Cost) per Week, and Initial Savings (or Cost). The following sections describe each type.

6.4.6.1 Savings (Cost) per Wafer Pass

Savings which are accrued at each wafer pass are included in this category. One example of cash flows which would fall into this category is a reduction in the cost of a spare part. Since a spare has an identifiable lifetime, the cost of a spare can be divided by the number of wafer passes. If the cost of a spare is reduced while the number of wafer passes it can perform every hour remains constant, the cost per wafer pass for implementing an option is also reduced. For this reason, every time the machine processes a wafer, there is a cost savings.

As an example see Figure 6.9. In this scenario, the equipment can process wafers at a rate of 100 per hour. Each spare part lasts for 1000 wafers, and as a result, must be changed every 10 hours. Dividing the cost of each spare by the number of wafers it can process yields a cost per wafer pass of $0.002. If the spare part cost can be cut by 50%, this cost per wafer pass will be $0.001, in effect saving $0.001 every time a wafer is processed. Each opportunity for cost per wafer savings are added and displayed in the savings (costs) per wafer pass cell of the savings summary section. If the change results in an increased cost per wafer pass, or an additional cost, the number in the savings (costs) per wafer pass column will be negative, and displayed in parenthesis.

		Base Case (Existing Process)	Option 1	Projected Return		
	units	projected	projected	Savings / (Cost) per Wafer Pass	Savings / (Cost) per Week	One Time Savings / (Cost)
Spare Part Cost/Wafer Pass						
Spare Part Unit Cost	$/part	$2.00	$1.00			
Parts/Tool	#/tool	1	1			
Wafers pass between part replacement	wafer pass	1000	1000			
Time between part replacement	hrs					
Parts used per week/tool	#	16.8	16.8			
Cost/wafer pass	$/wafer pass	$0.002	$0.001	$0.001		
Process Equipment Data						
Wafer Pass per Hour	wafer pass/hr	100	100			

Figure 6.9: Savings (Costs) per Wafer Example

6.4.6.2 Savings (Cost) per Week

Some cash flows in the *Equipment Change Impact Model*, such as labor costs, are modeled as weekly savings or costs. The most applicable type of weekly labor requirement is the applied time that technicians need to perform preventative maintenance or react to equipment downtime. Figure 6.10 shows an example of how labor is calculated.

In this example the time needed to perform a minor PM is reduced by 50%, from 2 hours to 1 hour. Since the PM schedule is based on the number of wafer passes performed, the extra time created by the PM time reduction actually causes the *frequency* of minor PMs to increase. The total time needed by the technicians to perform the maintenance decreases, however, from 6.6 total hours to 3.3 total hours per week. This is a savings of 3.3 hours per week. The labor savings (costs) cells for every scheduled and unscheduled maintenance type are then added and displayed in the summary section.

		Base Case (Existing Process)	Option 1	Projected Return		
	units	projected	projected	Savings / (Cost) per Wafer Pass	Savings / (Cost) per Week	One Time Savings / (Cost)
Process Equipment Data						
Wafer Pass per Hour	wafer pass/hr	10	10			
Minor PM						
Mean wafers between minor PM	wafer pass	1000	1000			
Time to perform minor PM	hrs/PM	2	1			
Additional Material Cost per minor PM	$/PM					
# Technicians needed to perform minor PM	#	2	2			
Wafer based minor PM frequency	PM/wk	1.6	1.7			
Minor PM technician time per week	hrs/week	6.6	3.3		3.3	

Figure 6.10: Weekly Savings (Costs) Example

6.4.6.3 Initial Savings (Costs)

For many projects there is a one time initial cost that is incurred at the beginning of a project. The cost captured in the cost of change section, which includes the initial labor resources and material costs needed to identify and justify a change, is one example. A one time R&D payment to a supplier is another. As a result, the initial savings cell in the savings summary section is often represented as a negative cash flow, in parenthesis. At times this cell may be positive, representing an initial savings, if there is an initial benefit to the project. Elimination of a piece of capital equipment, discussed in detail below, is one example of an initial savings as a result of project implementation.

6.4.6.4 Capital Expenditures: A Special Case

Investments in capital, such as an additional equipment set, result in two types of cash flows: an initial cost, and a yearly depreciation tax shield benefit. When a piece of equipment is added to a factory as a result of a proposed change, the initial cost is simply the cost of the equipment set and is represented as a negative cash flow in parenthesis. The depreciation tax shield benefit is savings in taxes as a result of the depreciation expenses on the accounting books. This can be found by dividing the total investment by the total number of weeks in the depreciation period and multiplying by the corporate tax rate. The *Equipment Change Impact Model* assumes a four year depreciation period and a corporate tax rate of 34%.[23] If a change results in the elimination of an equipment set (if throughput is dramatically reduced, for instance) the financial result can be modeled as an initial savings and a yearly depreciation tax cost.[24] Floor space is treated in a similar manner.

Figure 6.11 shows an example where an equipment set is eliminated. Notice that this elimination results in a floor space savings as well as an equipment savings. In this example one piece of equipment, valued at $10,000 can be eliminated. Each piece of equipment uses 100 square feet of floor space. The spreadsheet calculates the initial savings, which is $11,800 and $10,000 for the floor space and equipment investment savings, respectively. The depreciation tax shield benefit for the floor space reduction is divided into weekly cash flows and is computed by the following equation:

		Base Case (Existing Process)	**Option 1**	**Projected Return**		
	units	projected	projected	Savings / (Cost) per Wafer Pass	Savings / (Cost) per Week	One Time Savings / (Cost)
# of equipment sets in factory	#	2	1			
Total Floor Space Needed/Equipment	Square Feet /equipment	100	100		**($19.29)**	**$11,800**
Capital Cost/Equipment	$/equipment	$10,000	$10,000		**($16.35)**	**$10,000**

Figure 6.11: Equipment Reduction Example

---

[23] The depreciation period, corporate tax rate, and other constants can by easily changed in the spreadsheet by changing the values in a separate worksheets called constants. This gives the user the ability to change the assumptions of the model in one consolidated place without the need to change each formula in the spreadsheet individually.

[24] There is a depreciation tax shield cost because if the project had not been done, the corporation could have saved an amount in taxes equal to the depreciation expense per year.

$$DepreciationCashFlow_{Floorspace} =$$

$$\frac{\left[\frac{Sq.Ft.}{Equip.}\times\frac{\$}{Sq.Ft.}\left(\#\,Equip._{Option}-\#\,Equip._{BaseCase}\right)\right]}{DepreciationPeriod(weeks)}\times CorporateTaxRate \qquad (6.20)$$

The depreciation tax shield benefit for the equipment reduction is found in a similar manner by the equation:

$$DepreciationTaxShield_{Equipment} =$$

$$\frac{\left[\frac{\$}{Equip.}\left(\#\,Equip._{BaseCase}-\#\,Equip_{Option}\right)\right]}{DepreciationPeriod(weeks)}\times CorporateTaxRate \qquad (6.21)$$

6.4.6.5 Cash Flows Section Summary

The following table summarizes the three major cash flow summary columns, and list the information that is reflected in each column. These three columns present an itemized list of the savings and costs occurred in every category of the spreadsheet. The summary section, which will be described in the next section, adds these columns and presents an evaluation of a project's financial return.

Savings (Cost) per Wafer Pass	**Savings (Cost) per Week**	**Initial Savings (Cost)**
Scheduled Maintenance Material Costs	Scheduled Maintenance Labor Costs	Capital Expenditures
Unscheduled Maintenance Material Costs	Unscheduled Maintenance Labor Costs	Cost of Change
Monitor Wafer Costs	Depreciation Tax Shield Benefits	R&D Expenditures
	Line Yield	Supplier Quality Evaluation
	Revenue Opportunity Costs	
	Site Buyer Resource	

Figure 6.12: Cash Flow Summary Table

6.5 Sensitivity Analysis: The Best and Worst Case Scenarios

One of the advantages of the *Equipment Change Impact Model* over traditional total cost analysis worksheets in place at Intel is the ability to calculate the best and worst case scenario situations based on the variability of the data used in the model. Since most of the entries will be estimates, with a wide range of confidence limits, this ability can be very useful. The following example shows how the spreadsheet calculates the best and worst case scenarios.

Suppose that a team is investigating a change to the design of a spare part which will increase its life from 100 wafer passes between replacement to 1000 wafer passes between replacement. The unit cost of the spare part is not $20, but since it needs to be replaced so often, and the factory buys a high quantity, the factory occasionally receives 20% discount on the price of the spare. The new spare part has been quoted at the same price by another supplier, but the team feels that this price may go up as much as 50% in the next 3 years. Figure 6.13 illustrates how the team can fill out the Spare Part Cost/Wafer Pass section of the Financial Impact Worksheet to reflect this information.

The 20% entry in the spare part unit cost base case "- error" column is used to indicate that the price could drop below the projected value as much as 20%. The 50% entry in the spare part unit cost option 1 "+ error" column is used to indicate that the price could be increased above the projected value as much as 50%. Note that the cost/wafer pass row indicates what impact this variation has on the cost per wafer pass. For the base case, projected values result in a cost of $0.20 per wafer pass, but can drop as low as $0.16 due to variation of input values. For option 1 the projected values result in a $0.02 cost per wafer pass, but can be as high as $0.03 when the spare part price increases by 50%.

		Base Case (Existing Process)			**Option 1**		
	units	projected	+ error (%)	- error (%)	projected	+ error (%)	- error (%)
Spare Part Cost /Wafer Pass							
Spare Part Unit Cost	$/part	$20		20%	$20	50%	
Parts/Tool	#/tool	1			1		
Wafers pass between part replacement	wafer pass	100			1000		
Time between part replacement	hrs						
Parts used per week/tool	#	16.8	16.8	16.8	1.7	1.7	1.7
Cost/wafer pass	$/wafer pass	$0.20	$0.20	$0.16	$0.02	$0.03	$0.02

Figure 6.13: Sensitivity Analysis Example 1

The projected cash flow for this change is a savings of $0.18 per wafer pass ($0.20-$0.02). In the worst case, the base case cost/wafer pass projected value will be overestimated and the option 1 cost/wafer pass projected value will be underestimated. Thus, the team only saves $0.13 per wafer pass ($0.16-$0.03). in the worst case. In the best case, the team will have underestimated the base case cost/wafer pass and overestimated the option 1 cost/wafer pass. Since there is no variation between the "+ error" and "projected" columns of the base case cost/wafer pass, and no variation between the "- error" and "projected" columns of the option 1 cost/wafer pass, the best case cash flow equals the projected cash flow value. Fig 6.14 shows a summary of these results.

Projected Return	Best Case	Worst Case
Savings / (Cost) per Wafer Pass	Savings / (Cost) per Wafer Pass	Savings / (Cost) per Wafer Pass
$0.18	$0.18	$0.13

Figure 6.14: Results summary for Example 1

Instead of having variation in the spare part unit cost, there may be a case when the wafer pass between part replacement estimation can vary. Consider an example where the spare in use today lasts for 100 wafer passes on average, but has lasted for 110 passes on occasion. The improved spare may have a published life of 1000 passes, but since the team does not have experience with this spare, they estimate that the spare may only last for 800 wafer passes in the worst case. Figure 6.15 illustrates how the team can fill out the Spare Part Cost / Wafer Pass section of the Financial Impact Worksheet to reflect this information.

		Base Case (Existing Process)			Option 1		
	units	projected	+ error (%)	- error (%)	projected	+ error (%)	- error (%)
Spare Part Cost /Wafer Pass							
Spare Part Unit Cost	$/part	$20			$20		
Parts/Tool	#/tool	1			1		
Wafers pass between part replacement	wafer pass	100	10%		1000		20%
Time between part replacement	hrs						
Parts used per week/tool	#	16.8	16.8	15.3	2.0	2.1	1.7
Cost/wafer pass	$/wafer pass	$0.20	$0.20	$0.18	$0.02	$0.03	$0.02

Figure 6.15: Sensitivity Analysis Example 2

In this case 10% and 20% are entered in the appropriate "+ error" and "- error" columns of the spreadsheet. Notice that a "+ error" variation in the wafer pass between part replacement metric leads to "- error" in the parts used per week/tool. The spreadsheet automatically determines whether variation of an input metric results in a "+ error" or "- error" calculated value. This simplifies the spreadsheet, making the calculation for best and worst case the same, regardless of input value variation.

Given these results, best and worst case scenarios are calculated as $0.18 and $0.15 respectively. Fig 6.16 gives a summary of these values.

Projected Return	Best Case	Worst Case
Savings / (Cost) per Wafer Pass	Savings / (Cost) per Wafer Pass	Savings / (Cost) per Wafer Pass
$0.18	$0.18	$0.15

Figure 6.16: Results summary for Example 2

Of course any combination of "+ error" and "- error" cells may be used to reflect the variation in the projected value in any given situation. Just as in the projected value case, the best and worst case scenario have three separate cash flow columns for cost/wafer pass, cost per week, and initial costs. The best and worst case scenarios also have their own summary sections on the spreadsheet. This gives teams an ability to show the range of possible values in any given situations, and may highlight a metric where variation reduction, or more testing is necessary before project approval is warranted.

6.6 Financial Impact Worksheet Summary

Using the information contained in the cash flow columns, the Financial Impact Worksheet prepares summary information for the Projected Return, the Best Case, and the Worst Case section. Figure 6.17 shows the summary section for the Projected Return case. The first three rows of the summary section is the summation of cash flows for the initial savings (cost), weekly savings (cost), and savings (cost) per wafer pass columns. The fourth row is the summation of all technician labor hours for scheduled and unscheduled downtime saved as a result of the change (or additional technician time needed if PM time is increased). This row is printed for information only and does not impact savings unless the total number of labor hours saved is greater than one person. This is due to the fact that the Financial Impact Worksheet assumes headcount cannot be reduced unless one person from each shift can be eliminated (or his or her time can be used in another part of the factory), so labor savings under the 168 hour threshold (24 hours/day, 7 days/week) will not result in a dollar savings. Similarly the model assumes that headcount will not be added unless one person is needed on all shifts. If a person needs to be added, or can be removed from the process area, a cost or savings will appear in the fifth row of the

		Projected Return		
	units	Savings / (Cost) per Wafer Pass	Savings / (Cost) per Week	One Time Savings / (Cost)
Summary				
Total Initial Savings (Cost) of Change	$			($1,000)
Total Weekly Savings (Cost)	$/week		$1	
Total Savings (Cost) per wafer pass per tool	$/wafer pass	$0.50		
Technician Labor hours savings (cost)/week	hrs/week		42.0	
Technician headcount savings (cost) /week	$/week		$0	
Total Savings/week	$/week		$51	

Figure 6.17: Financial Impact Worksheet Summary Section

summary section, in the headcount savings (cost) /week cell. The final row of the summary section is a total weekly savings as a result of the change, and includes the weekly savings cell, the savings per wafer pass cell adjusted for the amount of wafers processed every week, and the labor savings cell.

6.6.1 Net Present Value and Payback Period Calculations

The Financial Impact Worksheet uses net present value to estimate the projected return of a proposed project. A standard measure, return on investment (ROI), is not used since the possible range of cash flows can be either negative or positive, causing complexity in programming for a general use spreadsheet. Net Present Value, or NPV, uses positive and negative cash flows in order to calculate a positive or negative return on investment. The NPV calculation compares the net present value of future cash flows to money invested at the hurdle rate (the model uses 14%, though this constant can be easily changed in a separate constants worksheet). If the Net Present Value calculation is positive, the present value of future cash flows are greater than the initial cash outlay invested at a 14% interest rate. The NPV can be expressed by equation 6.22.

$$NPV = \sum_{i=1}^{n} \frac{values_i}{(1 + rate)^i} \tag{6.22}$$

Where

n = # of years in time period being analyzed
values = individual cash flows
rate = hurdle rate (in this case 14%)

The spreadsheet calculates NPV after three time periods, one, two, and three years, and displays the result as either positive or negative. Figure 6.18 shows the NPV section for the cash flows summarized in Figure 6.17.

Projected Return		
Net Present Value, NPV (after one year)		Positive
Net Present Value, NPV (after two years)		Positive
Net Present Value, NPV (after three years)		Positive
Recovery period (at est. wafer pass/week)	weeks	19.6
Process Wafer Risk	$	$0

Figure 6.18: Projected Return for Figure 6.17

The NPV/payback period section also calculates the recovery period for a given project, which is the time is takes to earn back the initial investment. This metric can be very useful to teams, especially in rapidly changing technologies where equipment will be sold or upgraded in a short amount of time. To calculate the recovery period in weeks the spreadsheet uses the following formula:

$$\mathrm{Re\,cov}\,eryPeriod(weeks) = TimeToChange(weeks) \times \frac{InitialInvestment(\$)}{TotalSavings(\$)\big/_{week}} \qquad (6.23)$$

Finally, the NPV/payback period section reports the process wafer risk entered by the user in the cost of change section. This line is designed to give management a complete picture of the expected return and risks of implementing a proposed change.

The Financial Impact Worksheet also includes a summary and NPV/payback period section for the best and worst case scenarios, using the Best and Worst Case cash flow columns for the calculations.

Chapter 7 gives several examples of how the Financial Impact Worksheet can be used by improvement teams, and points out some of the advantages of using this model for data analysis.

Chapter 7

Applications of the Equipment Change Impact Model

The preceding chapters have explained in detail the equations and algorithms contained within the *Equipment Change Impact Model.* The purpose of this chapter is to present various examples of how the *Equipment Change Impact Model* can be used to make better decisions about process equipment modifications. The case studies which are presented are actual cases at Intel, but the data in each have been changed to protect the proprietary nature of Intel's cost structure.

7.1 Determining actual utilization rates

One feature of the *Equipment Change Impact Model* is the built-in algorithms which determine utilization capability and compute actual utilization. This feature can be especially helpful when analyzing factory capacity and work-in-process flow, and may be helpful for determining a possible bottleneck. In one case at Intel, the model helped to determine the impact of a high failure rate spare part, surfacing a potential factory bottleneck.

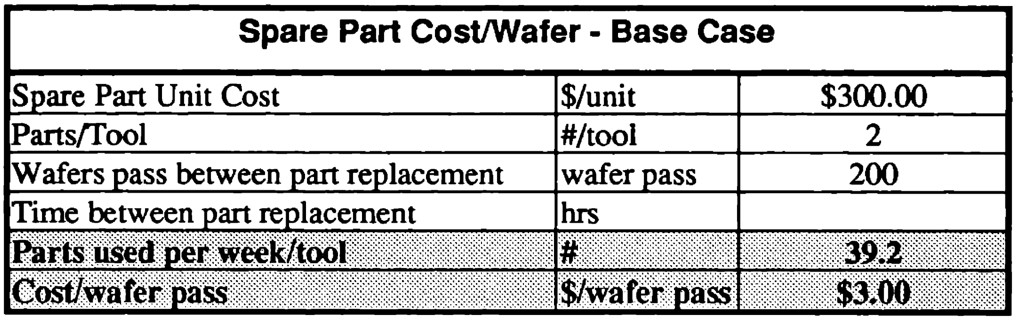
This team was working on a development project, in the beginning stages of process improvement before equipment was installed in a new factory. The team was concerned about a particular spare part, and in particular, the effect it would have on utilization. The problem with the spare part was immediately obvious to the experienced team members: it needed to be replaced every 200 wafer passes[25]. At the same time, the equipment manufacturer had a 80% utilization rate published in specification sheets. The team knew that the performance of the spare needed to be improved, but did not know a realistic goal for the spare part life which would avoid a factory bottleneck. Many of the team members

---

[25] The actual numbers presented in this case have been altered to protect Intel proprietary cost structure. The problem descriptions and outcomes of analysis are factual.

were concerned with the high cost of the spare part with such a high replacement rate, and wanted to look at second sourcing options.

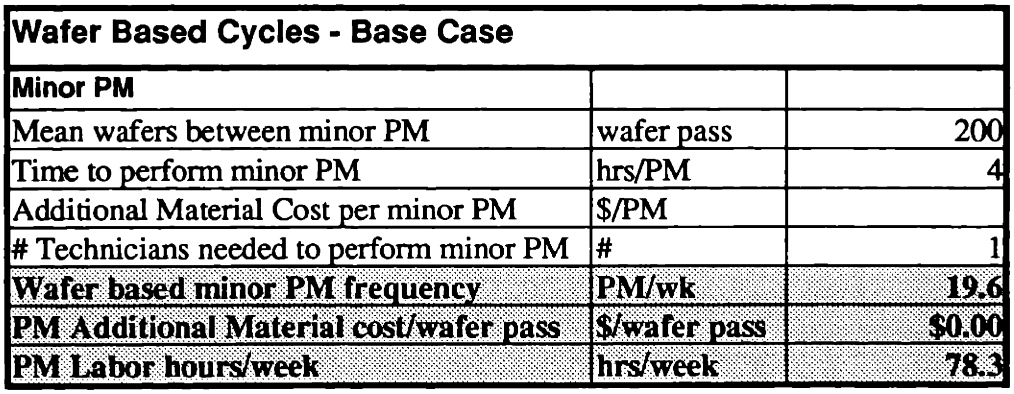
Based on the information known the team could use the *Equipment Change Impact Model* to assess the criticality of the situation, and direct task force effort. Figure 7.1 shows the Spare Part Cost/Wafer section of the model with the data entered for this situation.



Spare Part Cost/Wafer - Base Case		
Spare Part Unit Cost	$/unit	$300.00
Parts/Tool	#/tool	2
Wafers pass between part replacement	wafer pass	200
Time between part replacement	hrs	
Parts used per week/tool	**#**	**39.2**
Cost/wafer pass	**$/wafer pass**	**$3.00**

Figure 7.1: Spare Part Cost/Wafer

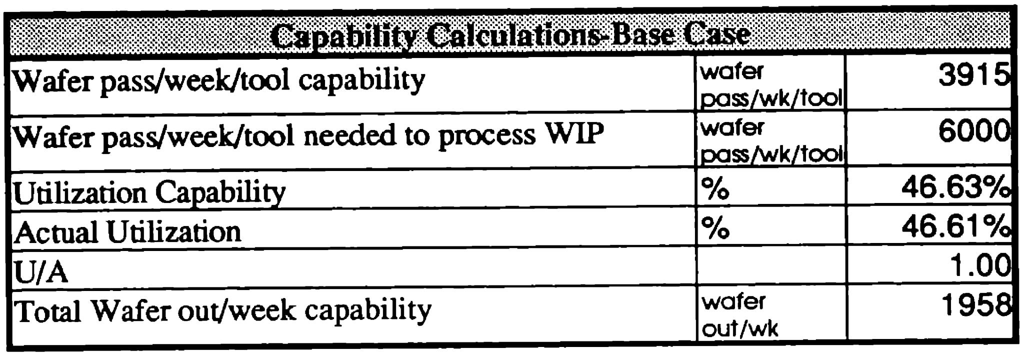
Notice that in this case there are 2 spare parts needed for every piece of equipment. The team must also enter the downtime information in the Wafer Based Cycles section, since replacement was scheduled every 200 wafer passes. Figure 7.2 shows how to enter data in this section. Notice that every time a spare must be replaced, it takes 4 hours of factory time. Although not shown here, the team will have to enter additional downtime information, since time based monitor checks, annual, and semi-annual PM were performed on this particular piece of equipment.



Wafer Based Cycles - Base Case		
Minor PM		
Mean wafers between minor PM	wafer pass	200
Time to perform minor PM	hrs/PM	4
Additional Material Cost per minor PM	$/PM	
# Technicians needed to perform minor PM	#	1
Wafer based minor PM frequency	**PM/wk**	**19.6**
PM Additional Material cost/wafer pass	**$/wafer pass**	**$0.00**
PM Labor hours/week	**hrs/week**	**78.3**

Figure 7.2: Minor PM Input Section

Suppose that the factory had planned to run 3000 wafers through the factory per week, and that this particular station was needed to process 2 separate layers during each wafer fabrication. In this case, every machine needed to be able to process 6000 wafer passes per week. As Figure 7.3 shows, the *Equipment Change Impact Model* determines that the maximum capability of the equipment, given the necessary downtime, can only reach 3915 wafers per week, resulting in 46.61% utilization.



Capability Calculations-Base Case		
Wafer pass/week/tool capability	wafer pass/wk/tool	3915
Wafer pass/week/tool needed to process WIP	wafer pass/wk/tool	6000
Utilization Capability	%	46.63%
Actual Utilization	%	46.61%
U/A		1.00
Total Wafer out/week capability	wafer out/wk	1958

Figure 7.3: Capability Calculations

Thus, the equipment creates a factory bottleneck and can only produce 1958 wafers in any given week, given no unscheduled downtime. Based on the model results, the team immediately knew that there was a problem beyond the abnormally high cost of the spare parts; they would need to buy 2 more equipment sets in order to process the planned wafer start rate.

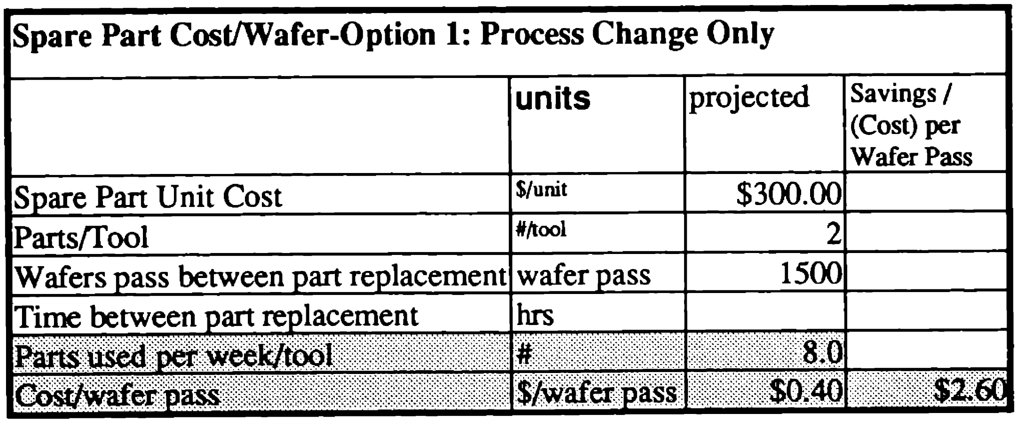
7.2 Determining a Process Improvement Goal

At this point in the project the team has determined that a critical adjustment to the process equipment must be made in order to avoid creating a factory bottleneck. The *Equipment Change Impact Model* can now be used to find out the spare part life that is necessary to achieve the 6000 wafer pass/week target rate.

To do this the team can use the *Goal Seek* feature of Microsoft Excel 5.0. This feature uses a process of iteration to adjust the contents of a cell until a formula dependent on that cell reaches a specified goal. To do this, first select the Total Wafer Out/Week Capability cell. Then select the *Goal Seek* function under the tools menu. An input block with then appear asking for the value that the user would like to have in the Total Wafer Out/Week Capability cell. The user should enter 3000 (or 6000 wafer passes/week since every wafer requires 2 passes). The input cell then asks which cell to vary in order to reach that number. The user should select the Mean Wafers between Minor PM cell, since this is the attribute of the maintenance schedule that the team is trying to affect. After pressing O.K., the program will search until it finds the value for Mean Wafers between Minor PM which yield 3000 wafers/week output rate. In this case the result is 369 wafers between minor PM. The team now has a tangible goal.

7.3 Evaluating a Proposed Change

The Intel team made remarkable progress toward its goal: The team achieved a Mean Wafer between Minor PM of 1500 wafers,[26] far in excess of the 369 wafer goal. They did this by making a modification to the equipment itself, rather than the spare part. This modification required an initial investment, and a required approval from the change control board, but the team felt that the change would be more than justified financially. The *Equipment Change Impact Model* could then be used to determine the actual NPV and payback period for this change.



Spare Part Cost/Wafer-Option 1: Process Change Only

	units	projected	Savings / (Cost) per Wafer Pass
Spare Part Unit Cost	$/unit	$300.00	
Parts/Tool	#/tool	2	
Wafers pass between part replacement	wafer pass	1500	
Time between part replacement	hrs		
Parts used per week/tool	#	8.0	
Cost/wafer pass	$/wafer pass	$0.40	$2.60

Figure 1: Spare Part Cost/Wafer: Option 1

---

[26] Although the data in this example has been altered, the actual team at Intel did arrive at a significant improvement.

To do this the team should enter the 1500 wafer pass information in both the Spare Part Cost/Wafer section of the spreadsheet as well as the Minor PM section for option 1 (see Figure 7.4 for an illustration of the Spare Part Cost/Wafer section).

Notice that $2.60 per wafer pass is saved by making this change. Since 6000 wafer passes will be performed weekly we can immediately tell that the savings will be substantial. The team should then fill out the initial investment and cost of change sections to account for the costs of the project. Figure 7.5 shows the summary section after this data is entered. The savings per week is nearly $7,827 and results in a positive NPV after one year.

Summary- Option 1: Process Change Only

	units	Savings / (Cost) per Wafer Pass	Savings / (Cost) per Week	One Time Savings / (Cost)
Total Initial Savings (Cost) of Change	$			($145,650)
Total Weekly Savings (Cost)	$/week		$0	
Total Savings (Cost) per wafer pass per tool	$/wafer pass	$3		
Technician Labor hours savings (cost)/week	hrs/week		66.1	
Technician Manpower savings (cost) /week	$/week		$0	
Total Savings/week	$/week		$7,827	

Figure 7.5: Summary, Process Change Only

At the 3000 wafer/week production rate, the payback period for the change is under one year, and the recovery period is 46.6 weeks. For the team this was an affirmation of the impact of the change and was an impetus to implement the change as soon as possible.

7.4 Evaluating a Potential Second Source

Several members of the Intel team decided to evaluate a second sourcing option, which would reduce initial cost of the spare part. It also had the potential of improving delivery performance and communication ease, as the current source was a Japanese supplier, and the new source was located in the same city as one of Intel's major facilities. In order to qualify a second source, substantial resources are necessary to evaluate the company facilities, conduct tests on sample spare parts to ensure high quality levels, and integrate the new source into the Intel system. For this reason, the team wanted to be sure that second sourcing was a viable option. The *Equipment Change Impact Model* can be used to help assess this type of situation.

The first step is to use the qualitative analysis matrix to compare the current sourcing strategy, a single Japanese supplier, with the alternative source. Figure 7.6 shows the resulting scores. Notice that the spread between the Base Case and the Option is 46, just under the 50 point threshold recommended in Chapter 5.

Qualitative Analysis Results : Second Sourcing	
Base Case	**Option 1**
381	427

Figure 7.6: Qualitative Analysis Results

To augment the qualitative analysis, the team decided to use the Financial Impact Worksheet to further investigate this option. The new supplier quoted the spare part at $200 instead of $300, and the team assumed that the second sourcing effort would be tested and implemented after the process change. In this case, the life of the spare part is modeled as 1500 for both the base case and option 1. Figure 7.7 shows the marginal results of the project using these assumptions.

Projected Return: Spare Part Sourcing Change Only		
NPV (after one year)		Negative
NPV (after two years)		Negative
NPV (after three years)		Negative
Recovery period (at est. wafer pass/week)	weeks	392.1
Process Wafer Risk	$	$0

Figure 7.7: Projected Return: Second Sourcing

The recovery period for completing the second sourcing option alone took almost 400 weeks to pay back financially due to the extensive testing required to justify the change.

Adding a second source would also introduce variation into the system, especially if two sources were maintained simultaneously. For these reasons, the team decided not to pursue the second sourcing option. If they had only had the price decrease information and had not been able to use the ***Equipment Change Impact Model***, they may have decided to pursue the second sourcing option right away, wasting valuable time and effort.[27]

7.5 Determining Optimum Project Timing

There is one additional option that the team did not pursue; they could implement the second sourcing effort at the same time as the process change. This would require only one series of tests instead of two, reducing the total implementation costs in the Cost of Change section of the Financial Impact Worksheet. Figure 7.8 shows the results when the two changes are implemented together. Note that implementing both changes at once yields a higher NPV, and a slightly lower turnaround time than implementing the process change alone.

Projected Return-Both Changes		
NPV (after one year)		Positive
NPV (after two years)		Positive
NPV (after three years)		Positive
Recovery period (at est. wafer pass/week)	weeks	45.7
Process Wafer Risk	$	$0

Figure 7.8: Projected Return for Sourcing and Process Change Simultaneously

The are a few risks associated with implementing this option. The first is that testing two changes at once is not always the best approach, especially if statistical analysis is necessary. Making these changes at the same time could confound the testing results, and if the process parameters did become out of control during the testing phase, it may be

---

[27] There may be occasions where teams will pursue a second sourcing option for strategic reasons. In this case the team may choose to implement the project regardless of financial impact.

difficult to identify the root cause of the problem. The second point of concern is the relatively small impact that the second sourcing had on the turnaround time of the project, and the overall savings/week. Since the qualitative analysis results were marginal, and the spare part has a direct impact on the processed wafer quality, it may not be worth the risk to drive on with a second sourcing effort. It may be a better strategy to concentrate efforts on improving relations with the current source, and apply valuable engineering resources to another high return project.

7.6 Evaluating the Impact of Data Variability

Chapter 6 describes the best and worst case scenario analysis available in the *Equipment Change Impact Model.* This feature can be used to examine the Intel spare part improvement example even further. Suppose, as a result of the process improvement that the spare part could last for 1500 wafers in the best case but only 1000 wafers in the worst case. The average life of the spare part was 1200 wafers. Also, suppose that the investment necessary to implement the change was three times as expensive and that extra materials were required for the routine maintenance.

Figure 7.9 shows the Spare Part Cost per Wafer section which reflects this new scenario.

Spare Part Cost/Wafer: Sensitivity Analysis				
	units	projected	+ error (%)	- error (%)
Spare Part Unit Cost	$/unit	$400.00		
Parts/Tool	#/tool	2		
Wafers pass between part replacement	wafer pass	1200	25%	17%
Time between part replacement	hrs			
Parts used per week/tool	#	10.0	12.0	8.0
Cost/wafer pass	$/wafer pass	$0.67	$0.80	$0.53

Figure 7.9: Sensitivity Analysis Input

Figure 7.10 summarizes the results for the projected, best, and worse case scenarios using the assumptions stated above.

	Projected Results	Best Case Scenario	Worst Case Scenario
Savings/Week	$4527	$5427	$3628
NPV after one year	Negative	Positive	Negative
Payback Period	78.4	70.2	90.7

Figure 7.10: Sensitivity Analysis Results

Note that in this case there is a positive NPV only in the best case. Both the projected results and the worst case scenario have a negative NPV after one year. This result gives the team important information; they know that the 1200 wafer pass result is not good enough and that the costs are too high to justify the change. They also know that the best case scenario is justifiable and presents a good goal for project improvement. Further, they know that if the variability in spare part life can be reduced at the same time as shifting the mean to 1500, then the projected, best and worst case scenarios would all be financially justifiable.

7.7 Examining the Benefits of Proactive Maintenance

The examples presented in this chapter up to this point have all dealt with issues surrounding equipment spare part changes. The *Equipment Change Impact Model* can also be used to evaluate maintenance changes and the subsequent impact on reliability.

Consider a team who is evaluating a proposed change in maintenance strategy in order to reduce the high cost of spare parts, and to improve utilization. One approach is to reduce the frequency of preventative maintenance steps where a costly spare part is replaced, and increase monitor wafer checks to ensure that product quality is not adversely affected. This scenario assumes that in order to make this change, the team will need to perform extensive testing and validation of the process, as well as monitor the effect of reduced PM frequency on equipment reliability. Figure 7.11 shows an example of what the Minor PM section of the *Equipment Change Impact Model* would look like in this scenario.

Notice that the mean wafers between minor PM has been doubled, from 800 to 1600 wafer passes. This decrease in frequency creates two types of savings. The first is a

Minor PM		**Base Case**	**Option 1**	**Savings per Wafer Pass**	**Savings per week**
Mean wafers between minor PM	wafer pass	800	1600		
Time to perform minor PM	hrs/PM	12	12		
Additional Material Cost per minor PM	$/PM	$3,000	$3,000		
# Technicians needed to perform minor PM	#	2	2		
Wafer based minor PM frequency	PM/wk	**1.4**	**0.7**		
PM Additional Material cost/wafer pass	$/wafer pass	**$3.75**	**$1.88**	**$1.88**	
Minor PM technician time per week	hrs/week	**33.8**	**16.9**		**16.9**

Figure 7.11: Minor PM Strategy Changes

savings per wafer pass since the spare parts last longer, and their cost can be allocated over twice as many wafers. The second savings is a labor savings, which is calculated as hours per week by the *Equipment Change Impact Model.*

Figure 7.12 shows the monitor wafer section of the model. The team assumes that the monitor frequency should be the same as the previous PM schedule.

Monitor Steps		**Base Case**	**Option 1**	**+ Error (%)**	**Savings / Wafer Pass**	**Savings per week**
Mean wafer pass between monitors	wafer pass		800			
Wafer Based Monitor time	hrs		2	600%		
Test Wafers required / monitor	wafer pass		1			
Wafer based monitor frequency	#/wk	**0.0**	**1.4**	**1.4**		
Monitor wafer cost/wafer pass	$/wafer pass	**$0.00**	**$0.25**	**$0.25**	**($0.25)**	
Monitor labor hrs/week	hrs/wk	**0.0**	**2.8**	**19.7**		**-2.8**

Figure 7.12: Monitor Step Strategy Changes

Thus, instead of conducting a minor PM, the technicians will only need to perform a monitor step at every other PM cycle. The team also assumes that in some cases, after performing a monitor step, they may need to go ahead an perform an entire minor PM as a result of out of control cases. In this case, the team represents that risk by filling in the "+ Error" column of the wafer based monitor time. Notice that there is an increased monitor wafer cost to make this change as well as an additional labor cost of 2.8 hours/week.

With these inputs the *Equipment Change Impact Model* calculates the impact on utilization. As Figure 7.13 shows, the projected value for wafer pass/week/tool capability decreases to 1344 wafer pass/week/tool in the worst case because of the 600% variation in monitor step time. This does not cause capability to dip below the wafer pass/week/tool needed to process work-in-process, and has very little impact on the analysis.

Capability Calculations - Option 1		**Projected Value**	**Best Case**	**Worst Case**
Wafer pass/week/tool capability	wafer pass/wk/tool	1527	1527	1344
Wafer pass/week/tool needed to process WIP	wafer pass/wk/tool	1125	1125	1125
Actual Wafer pass/week	wafer pass/wk	9000		9000
Utilization Capability	%	90.91%		
Actual Utilization	%	66.96%		
U/A		0.74		
Actual Wafer out/week	wafer out/wk	3000	3000	3000

Figure 7.13: Capability Calculations after Maintenance Schedule Changes

The proposed change may have an impact on line yield, however. The team estimates that line yield loss may increase from 10% to 11% as a result of the change. Using a cumulative cost of $200, $6,000 additional dollars will be lost per week as a result of this change. Since the operation is clearly not a factory bottleneck (capacity exceeds production) there is no revenue opportunity cost of making this change.

Specific Process Line Yield Costs		Base Case	Option 1	Savings per week
Line Yield Loss	% wafers lost	10.00%	11.00%	
Wafer Cumulative Cost at that Step	$/wafer	$200	$200	
Line Yield Loss/week	$/week	$60,000	$66,000	($6,000)
Revenue Opportunity Cost				
Revenue/Wafer (Enter only if equipment is factory constraint)	$/wafer		$0	
Additional Revenue from Increased Throughput	$/week		$0	$0
Lost Revenue from Line Yield Loss/week	$/week		$0	$0

Figure 7.13: Line Yield Implications of Making Maintenance Changes

The results of this analysis are contained in Figure 7.14. Although there is an initial cost and a cost per week, in this case the savings per week is enough to justify this decision. The ***Equipment Change Impact Model*** calculates that the NPV of the project is positive after one year, with a payback period of 24.5 weeks.

Summary		Savings / Wafer Pass	Savings (Cost) week	Initial Savings (Cost)
Total Initial Savings (Cost) of Change	$			($12,770)
Total Weekly Savings (Cost)	$/week		($6,000)	
Total Savings (Cost) per wafer pass per tool	$/wafer pass	$2		
Technician Labor hours savings (cost)/week	hrs/week		14.1	
Technician headcount savings (cost) /week	$/week		$0	
Total Savings/week	$/week		$8,625	

Figure 7.14: Summary after Making Maintenance Changes

There are a few key elements that the team needs to consider before implementing this change. The first is the effect of the reduction in PM frequency on the long term life of the equipment. Second, if the initial PM frequency was determined by Weibull analysis, then statistically the existing PM strategy catches the predictable breakdowns of equipment. The risk with changing the PM frequency is that more breakdowns may equipment. The risk with changing the PM frequency is that more breakdowns may occur, causing unscheduled maintenance frequency to increase, which has not been considered in the example. Finally, if a monitor step does surface the need to do a complete PM, there will be an increased material charge, which has not been considered in this example.

7.8 Summary

This chapter has presented several uses for the *Equipment Change Impact Model*, but is not intended to be a conclusive list of all of the model capabilities. Some other applications of the model include changes from reactive to preventative maintenance and evaluating spare part cost ceilings prior to negotiation. As the tool begins to be proliferated at Intel, additional uses may surface.

Though the model is a good initial cost modeling tool, there are some limitations in the analysis that it can do. It is important that users of the model understand its capabilities as well as its weakness. Chapter 8 presents some of these limitations, and provides suggestions for future enhancements to the model.

Chapter 8

Summary

The preceding chapters have presented a generic framework for total cost improvement projects and introduced the *Equipment Change Impact Model,* which can help facilitate this process. Although this model was designed for Intel internal use, the basis of the model and its ideas can be easily adapted for use in other companies and industries. To proliferate this model successfully, users of this model, as well as future model designers, should understand the assumptions inherent in the *Equipment Change Impact Model*, and how these assumptions impact final analysis.

This chapter summarizes the assumptions made in the *Equipment Change Impact Model* and points to areas for future research. Ideas for similar total cost analysis tools, within and outside the semiconductor industry, are also presented.

8.1 Key Model Assumptions

The *Equipment Change Impact Model* includes several basic assumptions. These assumptions are made in an attempt to simplify the model for the user, as well as promote programming ease. Each of the following sections outlines the basic assumptions, pointing to opportunities for future improvement where necessary.

8.1.1 Utilization Assumptions

When calculating the actual utilization percentage, the model assumes that all of the work in process, or WIP, that is in the production pipeline will be ready to feed the process in question whenever that machine is available. In other words, the model does not take into consideration lag time, or scheduling complexity that may prevent the equipment from processing production material continually whenever available.

For instance, if an equipment set is available 80% of the time, and the amount of wafers planned for the factory in a given week requires a 75% availability, then the model assumes that the equipment set can process all of the wafers in the pipeline every time. There are instances in real factory scenarios where this is impossible.

As an example, consider a case where the equipment set that processes wafers just before the equipment set being analyzed goes down for maintenance. If there was no material available to process, the equipment set being analyzed would not be able to run, even though it was available. In situations like this the actual machine utilization will be lower than the calculation results from the *Equipment Change Impact Model.*

There are a few ways to handle this problem. One is to add more complexity to the model by adding additional sources of downtime, like idle or waiting time. This can be estimated on a weekly basis by collecting actual run time information from the factory. Another is to assume that the actual utilization will always be a certain percentage lower than calculated. The operational overhead section of the *Equipment Change Impact Model* anticipates that user may want to compensate for extra downtime, and allows the user to input a percentage of time that the machine is down for reasons not captured in the scheduled and unscheduled downtime sections.

8.1.2 NPV Analysis Assumptions

The NPV analysis makes the basic assumption that the lifetime of the base case project and the option 1 project is the same. This is driven by the format of the spreadsheet. The NPV is based on the savings and cost flows, which assume that the factory costs per wafer will remain constant for both the base case and option 1.

The problem with this assumption is that there are cases where the lifetime of equipment can be radically changed by completing a system upgrade. In these cases, the base case equipment configuration may only last for another 6 months, while an upgraded set could last for many more years. Thus, the *Equipment Change Impact Model* may calculate a lower NPV than could actually be realized, depending on the costs of the upgrade and the value of the equipment being replaced. For these special situations it may be necessary to adapt the summary section of this model in order to accommodate the project specifics. In most other cases the assumption of equal lives will not impact the analysis, especially if the goal is a positive NPV in the first year of implementation.

The second assumption that the *Equipment Change Impact Model* makes is a 0% inflation rate. This assumption is driven by the complexity of programming interest rate adjustments in the cash flow calculations. Although rationalized, this assumption is rarely justified, especially in the semiconductor industry.

Consider the cost of silicon and process equipment. Since its supply is controlled by a few number of key suppliers, it is reasonable to assume that price increases could occur quite easily, especially in a constrained market. The magnitude and timing of these shifts is difficult to predict and model in a generic spreadsheet, however. To capture any inflationary risk, I recommend using the sensitivity analysis. The "+ error" and "- error" columns can be used for all prices needed in the model, giving the user flexibility in analyzing a range of possible price changes.

8.1.3 Payback Period Metric Limitations

Payback period analysis, while used frequently in industry practice and included in this model, has some distinct disadvantages for measuring project viability. The first disadvantage is that the payback period calculation does not take the time value of money into account. As a result, a payback period may seem like a short amount of time, but depending on the interest rates, could be inferior to other types of investments.

The second disadvantage of the payback period metric is that it is insensitive to the timing of cash flows. For instance, the payback period calculation does not differentiate between a project that makes money late in the payback period cycle, and one that makes money immediately. In the latter case, the income from the project can be invested earlier, making this project more attractive.

The third disadvantage of the payback period metric is its insensitivity to cash flows occurring beyond the payback date. If a project plan calls for a capital investment that will be used for 10 years, and then sold for a significant salvage value, the salvage value can make the project more attractive. If the project payback period is only 6 years, then the salvage value of the capital equipment is irrelevant to the payback period calculation.[28]

The payback period does have some use, however, as a rough measurement of project risk. This is especially true in the semiconductor industry where rapid technology changes can obsolete an entire equipment set within a few years. In this case, projects that have payback periods which are outside the predictable future can be considered to be in the high risk category.

8.1.4 Die Yield Implications of Spare Part Changes

The one metric that is not included in the *Equipment Change Impact Model* is die yield. Die yield is defined as the percentage of good die per wafer. This attribute is highly dependent on the quality of the process, particle count, handling issues, and other factory variables. It is conceivable that changes which are being analyzed by the *Equipment Change Impact Model* will also affect die yield.

In order to simplify the model, I have assumed that die yield impacts are analyzed separately from the model and that the maintenance schedule and spare part choices reflect a given die yield threshold. Thus, the purpose of the *Equipment Change Impact Model* is to analyze the difference in cost between two static conditions, each of which has the same die yield implications. This is analogous to assuming that die yield implications can be modeled as a step function, and that several maintenance and spare part choices will yield the same number of good die.

In actuality, die yield is a function of maintenance and spare part choices, and there may be small incremental improvements in maintenance procedures which will have a great impact on die yield, and anticipated revenue. Future research in this area and the addition of die yield implications to this model is suggested.

---

[28] Higgens, Robert C. Analysis for Financial Management. New York: Irwin, 1992

8.2 Suggestions for Future Proliferation

One of the key challenges in developing the *Equipment Change Impact Model*, was to ensure its use and proliferation throughout Intel. The following sections summarize key learnings and provide suggestions for future tool designers.

8.2.1 Identify a Product Champion with High Level Support

In order for the proliferation stage of a project to be successful, it is important to have one person in the organization as the primary tool owner. That person should be responsible for distribution, maintenance, and documentation of the tool. He or she may need to assign upgrades to another technical expert if necessary. The important qualities for the champion are enthusiasm, and a good working knowledge of the tool. The product champion for the *Equipment Change Impact Model* is a permanent member of the Capital Acquisition group. She had the extra advantage of management support for the project, and was able to add the new responsibilities to her yearly task list.

8.2.2 Train Super Users in Key Functional Areas

In addition to a product champion, it is helpful to train users in key functional areas. The goal is to have these individuals develop into expert users, or super users, who can then help to train others in their respective areas. Process Equipment Development (PED) was one department of Intel which was targeted for super users. This is a key department since most of the continuous improvement teams throughout Intel are led by its members. In addition to PED, members of Industrial Engineering, Process Engineering, and Finance were also trained in the use of the tool.

The added benefit of training users in key functional areas is the informal proliferation that occurs when a super user encounters a potential application for the tool as part of his or her job function. During departmental meetings, or other informal conversations, he or she may suggest the tool to other colleagues. This type of proliferation is a bottoms up approach, and can help to proliferate a new tool through a grass roots effort. Combined with high level commitment, this approach can be very successful.

8.2.3 Convince Key Decision Makers of Model Value

In addition to proliferation at the working level, high level management should be convinced of the advantages of a new tool. There are two reasons why this is helpful. The first is that managers can add the training for the tool to departmental budgets and to personnel training plans. Second, managers can ask for the analysis that the tool provides when approving major changes. In the case of the *Equipment Change Impact Model*, the model and its uses was also reviewed with the change control board chairpeople. Since they make decisions regarding important equipment modifications, their endorsement of the tool was essential.

8.2.4 Provide Training, Upgrades and Easy Access to the Tool

The training necessary for tool proliferation can be easily underestimated. Since it is impossible for the designer to explain the tool personally to every potential user, clear documentation is essential. On-line help functions can be extremely helpful, as are application examples and training kits. The effort required to complete effect training can be as much as or more than the time it takes to generate the tool and should be planned as early in the project cycle as possible.

The second aspect of any tool is that improvements will be suggested as more and more users become familiar with its use. For this reason, resources to implement upgrades should be identified.

Finally, proliferation can be facilitated through a network system or other distribution method. The *Equipment Change Impact Model* was designed using a software platform used throughout the Intel. Limiting the file size on any model can help to reduce transmission time and disk space.

8.3 Applicability to Other Industries

Although the *Equipment Change Impact Model* was prepared specifically for Intel, total cost analysis tools can be generated for a wide variety of companies and industries. Semiconductor equipment tool manufacturers represent one obvious industry where use of the model could be made with slight modification to the model. This type of analysis could also be applied to any industry where processing equipment represents a large percentage of process cost.

To generate a similar model the following steps should be followed:

8.3.1 Identify the sources of factory downtime

These sources of factory downtime should include scheduled and unscheduled downtime at least, but can also include idle time, set up time, transfer time between shifts, or non-utilized shifts as in the case of a two shift operation. The goal is to identify the major sources of downtime, without adding unnecessary complexity to the model.

8.3.2 Calculate utilization capability and actual utilization

Once all of the possible sources of downtime have been identified, the user can calculate the utilization capability of the equipment using a formula similar to 6.12, which is described in Chapter 6, section 6.4.1.3. Actual utilization should also be calculated by taking into account the planned material flow through a process step. Equation 6.14 found in section 6.4.1.4 of Chapter 6 provides one example of how this can be done.

8.3.3 Identify the sources of cost including spare parts, labor, and yield

The next step in model generation is the identification of routine cost sources. Although this may vary considerably from industry to industry, some examples of possible cost sources are equipment spare parts, machine yield or scrap rate, maintenance labor and production labor. Once an initial list is complied it is very helpful to review this list with a variety of functional areas to check for completeness.

8.3.4 Identify the possible costs needed to implement a change

One time costs associated with implementing a change should be identified in order to calculate a project return on investment. This section may include investment costs for additional capital purchases, marketing costs, resources necessary test changes and document results, and training costs. This section will be highly dependent on the change control policy of an organization, the type of industry where the change is being made., and in some cases the nature of the change being considered.

8.3.5 Calculate cash flows for the project

One all of the above items are determined, the model designer should incorporate algorithms to calculate the savings and cost cash flows when a change is made. These savings and costs can be divided by the actual utilization times throughput in order to evaluate the impact of projects which increase factory capacity. Section 6.4.6 in Chapter 6 is an example of one possible way to organize this section.

8.3.6 Calculate financial summary information

Once all of the cash flows have been identified, it is a fairly straightforward exercise to calculate the net present value of the project. Many spreadsheet programs, including Microsoft Excel, have a built in function that calculates these summary statistics. Other pertinent summary statistics include savings per week, and initial investment, and any project risk.

These steps provide a framework for creating a generic spreadsheet to calculate the total cost impact of making a change. Future users of the tool will be able to capture all impacts of process equipment changes, in addition to initial cost. Once successfully implemented, this tool will encourage more informed and consistent decision making across an organization.

Bibliography

Bentley, James. "Integrating Design and Manufacturing Strategies for Business Transformation." International Journal of Technology Management 6 (1991): 355-359.

Dance, Daren. "Applications of Cost-of-Ownership." Semiconductor International Sept. 1994: 6-7.

Davis, Tom. "Effective Supply Chain Management." Sloan Management Review Summer 1993: 35-46.

Dick, Andrew R. "An Efficiency Explanation for Why Firms Second Source." Economic Inquiry April 1992: 332-354.

Dowlatshahi, Shad. "Purchasing's Role in a Concurrent Engineering Environment." International Journal of Purchasing & Materials Management Winter 1992: 21-25.

Eschenbach, Ted G. "Quick Sensitivity Analysis for Small Projects and Feasibility Studies." American Associaltion of Cost Engineers Transactions 2 (1992): L.6.1-L.6.8.

Godfrey, Don. "Incorporating value analysis through a concurrent engineering program." Production 9 (1993): 44-47.

Gagne, Margaret L. "New product costing, Japanese style." CPA Journal May 1993: 68-71.

Goldratt, Eliyahu M. The Goal. Croton-on-Hudson: North River Press, 1948.

Lee, John Y. "Use target costing to improve your bottom-line." CPA Journal Jan. 1994: 68-70.

Hatty, Mark. "Potential Failure Modes and Effects Analysis: A business perspective." Quality Engineering 7.1 (1994-95): 169-186.

Higgens, Robert C. Analysis for Financial Mangement. New York: Irwin, 1992.

Ishikawa, Kaoru. Guide to Quality Control. Tokyo: Asian Productivity Organization, 1982.

Keeney, R.L. "New Industrial Product Design and Evaluation Using Multiattribute Value Analysis." Journal of Product Innovation Management 4 (1987): 185-198.

Mares, Moses. Equipment Change Control. Austin: SEMATECH, Inc, 1992.

Menon, Viju S. "A Constraint-based Systems Approach to Line Yield Improvement in Semiconductor wafer Fabrication." Masters Thesis MIT, 1994.

Nevins, J.L. and Whitney, D.E.. Concurrent Design of Products and Processes. New York: McGraw Hill, 1990.

Proctor, R.A. "Selecting an appropriate strategy: A structured creative decision support method." Marketing Intelligence & Planning 10 (1992): 21-24.

Schoemaker, Paul. "A Pyramid of Decision approaches." California Management Review Fall 1993: 9-31.

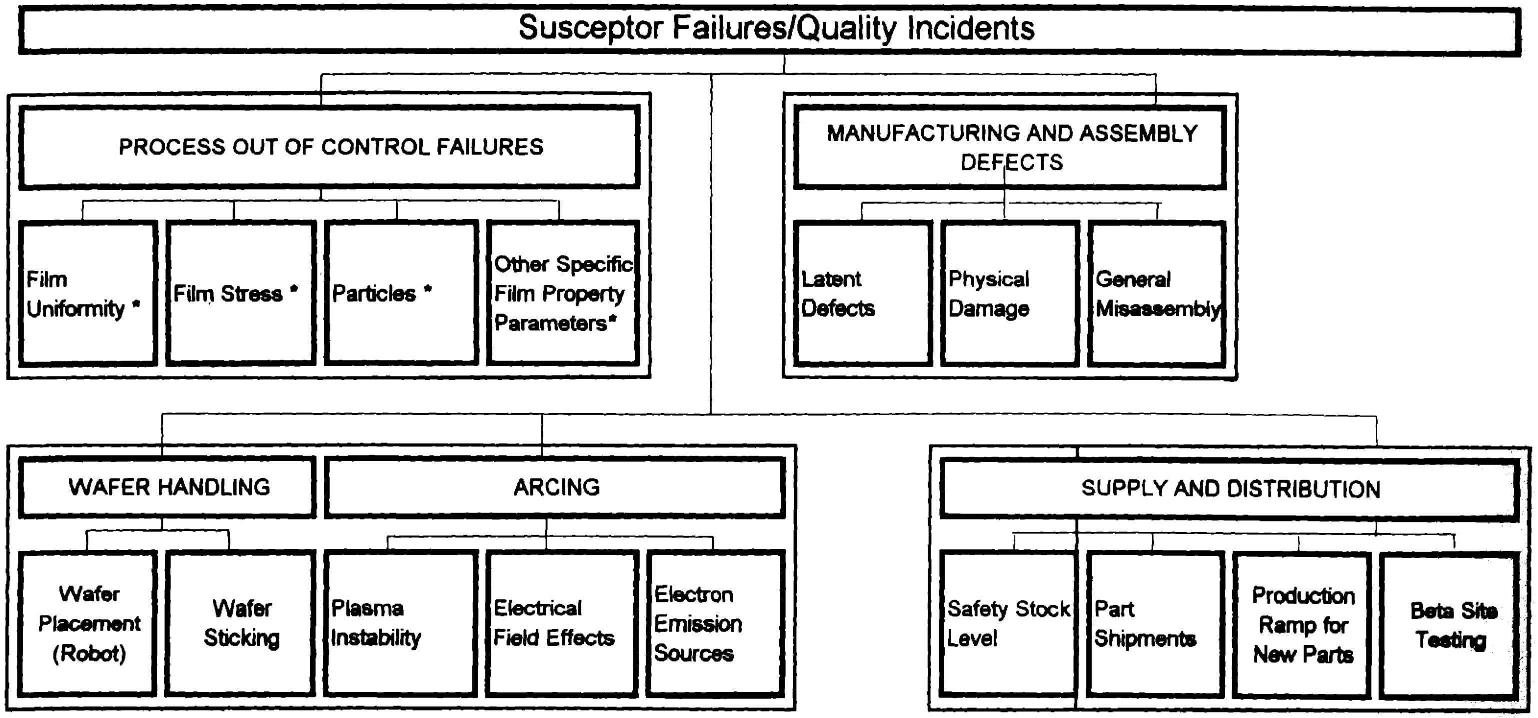
Tullous, Raydel and Utecht, Richard Lee. "Multiple or Single Sourcing?" Journal of Business & Industrial Marketing 7 (1992): 5-16.

Younker, Del L. "VE-Creative steps toward total cost control." Cost Engineering 35 Summer1993: 29-33.

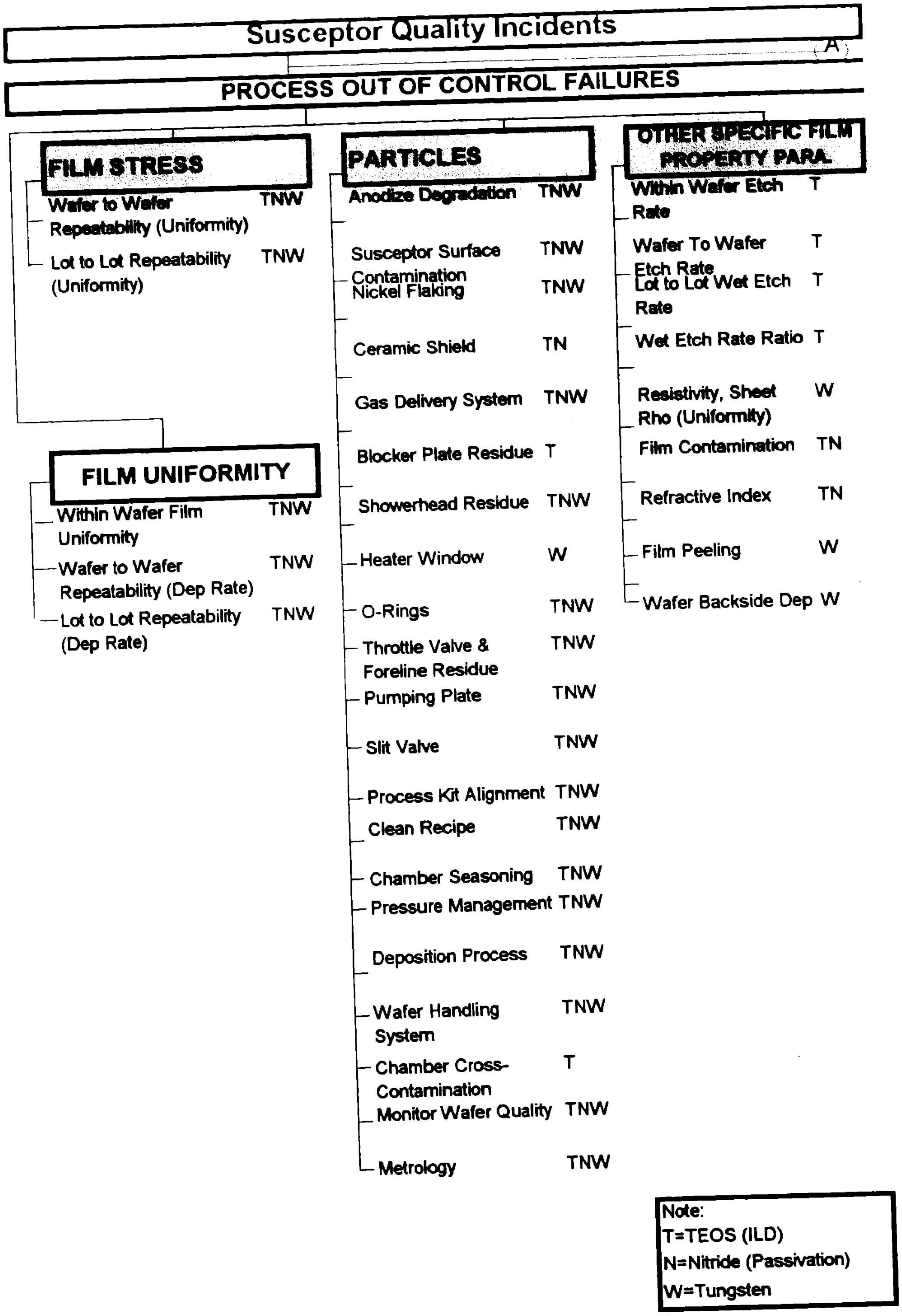
Williams, Alvin J. "Purchasing's Role in Value Analysis: Lessons from Creative Problem Solving." International Journal of Purchasing & Materials Management Spring 1992: 37-42.

Appendix A

Susceptor Fault Tree Analysis (FTA)



* Individual FMEA's developed for these causes


Susceptor Quality Incidents
A
PROCESS OUT OF CONTROL FAILURES
FILM STRESS
Wafer to Wafer Repeatability (Uniformity) TNW
Lot to Lot Repeatability (Uniformity) TNW
FILM UNIFORMITY
Within Wafer Film Uniformity TNW
Wafer to Wafer Repeatability (Dep Rate) TNW
Lot to Lot Repeatability (Dep Rate) TNW
PARTICLES
Anodize Degradation TNW
Susceptor Surface Contamination TNW
Nickel Flaking TNW
Ceramic Shield TN
Gas Delivery System TNW
Blocker Plate Residue T
Showerhead Residue TNW
Heater Window W
O-Rings TNW
Throttle Valve & Foreline Residue TNW
Pumping Plate TNW
Slit Valve TNW
Process Kit Alignment TNW
Clean Recipe TNW
Chamber Seasoning TNW
Pressure Management TNW
Deposition Process TNW
Wafer Handling System TNW
Chamber Cross-Contamination T
Monitor Wafer Quality TNW
Metrology TNW
OTHER SPECIFIC FILM PROPERTY PARA.
Within Wafer Etch Rate T
Wafer To Wafer Etch Rate T
Lot to Lot Wet Etch Rate T
Wet Etch Rate Ratio T
Resistivity, Sheet Rho (Uniformity) W
Film Contamination TN
Refractive Index TN
Film Peeling W
Wafer Backside Dep W
Note:
T=TEOS (ILD)
N=Nitride (Passivation)
W=Tungsten

Susceptor Quality Incidents

A B

MANUFACTURING AND ASSEMBLY DEFECTS

SUPPLIED HARDWARE NOT TO SPEC

- Cracked Ceramic (as received at Supplier)
  - packaging problems
  - base material composition wrong
    - specification misinterpretation
    - wrong heat cycle for cooking slurry
    - non-uniform slurry
    - stress buildup
  - poor machining techniques used
    - thin walls in part design
- Susceptor Plate Heat Treatment
  - skipped heat treatment
    - poor operator training
    - poor documentation
  - mis-stacking of piles during treatment
    - poor operator training
    - poor documentation
  - heat treatment control computer problem
  - missed chart recorder check
  - heat treatment timing too short
- Nickel Plating
  - skipped nickel plating step
    - several suppliers in supply chain
    - parts not shipped to plating
  - poor plating quality
  - poor cleaning by original machinist
  - wrong chemical composition

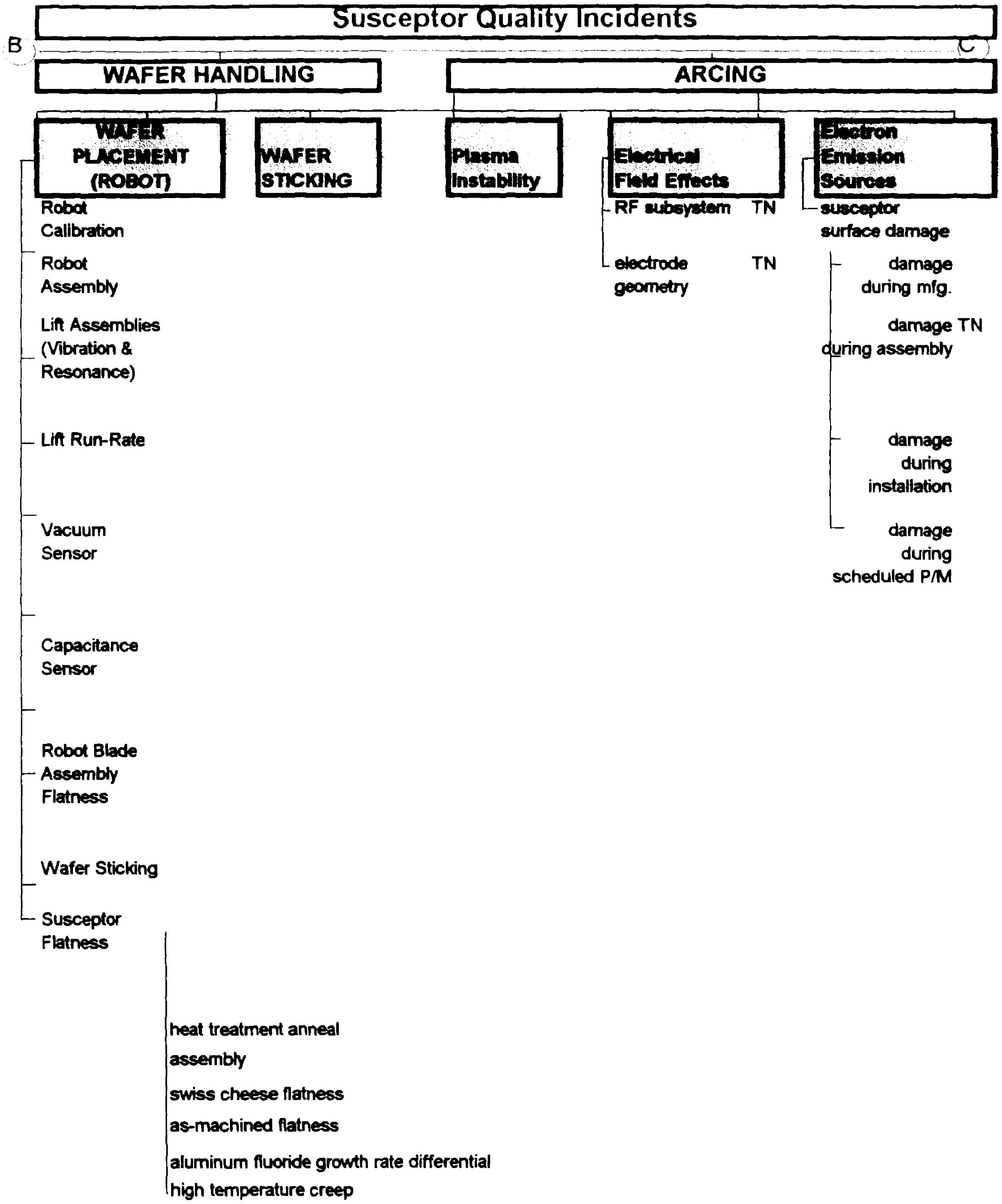
D

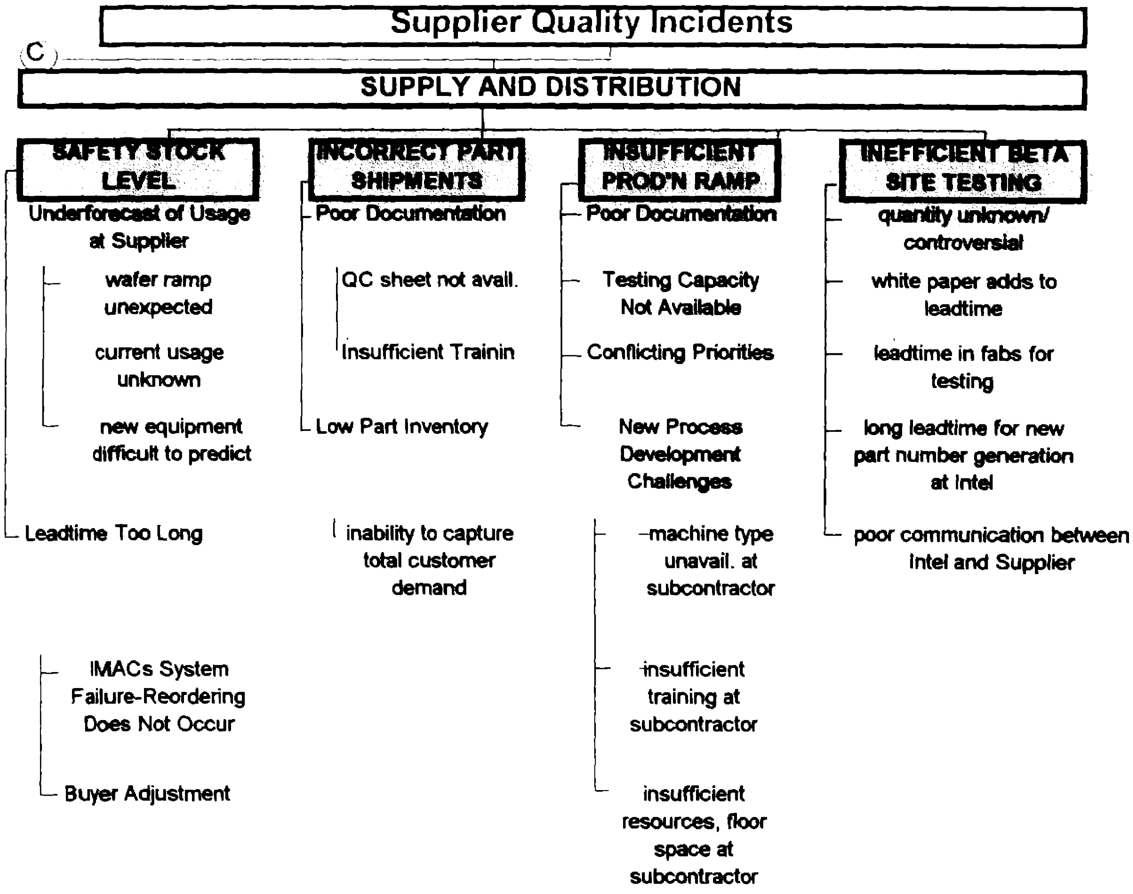
PHYSICAL DAMAGE

- Cracked Ceramic (during mfg., delivered to Intel)
  - mishandling
  - packaging problems
- Bent Susceptors
  - mishandling
- Surface Damage
  - damage during mfg.
  - damage during assembly
  - damage during installation
  - damage during scheduled P/M
- Thermocouple
  - twisted during assembly (decalibration)
  - shorted during assembly
  - open during assembly
  - grounded during assembly
- Susceptor Ground Strap Connection to Chamber Wall
  - loose connection
- Susceptor Ground Strap Fraying
  - ground strap rubbing on bellows (cable routing)
  - ground strap too short
- Susceptor Ground Strap Cable Broken
  - poor weld joint
  - excessive ground strap
- Susceptor Ground Boss to Tube Weld
  - poor weld joint
- Susceptor Ground Tube to Plate Connection
  - loose fasteners
  - fasteners overtightened (threads stripped)
  - incorrect fasteners used
  - stress relaxation of joint

GENERAL MIS-ASSEMBLY

- Loose Fasteners
  - torque spec incorrect
  - torque spec not followed
- Misaligned Swiss Cheese
  - loose fasteners
- Incorrect Hardware (Not to Spec.)
  - computer generates wrong paperwork
  - wrong paperwork picked
  - wrong part picked
- Thermocouple Installation
  - design difficult to assemble
  - operator error
- Missing Fasteners
  - wrong paperwork used
  - wrong part picked
- Missing O-Rings
  - insufficient operator training/experience
- cracked/loose ceramic
  - must pick and choose ceramic pins to fit
  - tolerances too tight for manufacturing


Susceptor Quality Incidents
B
C
WAFER HANDLING
ARCING
WAFER PLACEMENT (ROBOT)
WAFER STICKING
Plasma Instability
Electrical Field Effects
Electron Emission Sources
Robot Calibration
Robot Assembly
Lift Assemblies (Vibration & Resonance)
Lift Run-Rate
Vacuum Sensor
Capacitance Sensor
Robot Blade Assembly Flatness
Wafer Sticking
Susceptor Flatness
heat treatment anneal
assembly
swiss cheese flatness
as-machined flatness
aluminum fluoride growth rate differential
high temperature creep
RF subsystem TN
electrode geometry TN
susceptor surface damage
damage during mfg.
damage TN during assembly
damage during installation
damage during scheduled P/M


Supplier Quality Incidents
C
SUPPLY AND DISTRIBUTION
SAFETY STOCK LEVEL
Underforecast of Usage at Supplier
wafer ramp unexpected
current usage unknown
new equipment difficult to predict
Leadtime Too Long
IMACs System Failure-Reordering Does Not Occur
Buyer Adjustment
INCORRECT PART SHIPMENTS
Poor Documentation
QC sheet not avail.
Insufficient Trainin
Low Part Inventory
inability to capture total customer demand
INSUFFICIENT PROD'N RAMP
Poor Documentation
Testing Capacity Not Available
Conflicting Priorities
New Process Development Challenges
machine type unavail. at subcontractor
insufficient training at subcontractor
insufficient resources, floor space at subcontractor
INEFFICIENT BETA SITE TESTING
quantity unknown/ controversial
white paper adds to leadtime
leadtime in fabs for testing
long leadtime for new part number generation at Intel
poor communication between Intel and Supplier

D Anodize

- insufficient machine shop cleaning
    - cleaning step skipped
    - short cut of cleaning process
    - finger print from handling
- non uniform bead blast
    - operator error (human controlled)
    - malfunction with computer (computer controlled)
- wrong temp. bath
    - bath too hot
    - bath too cold
    - variation in bath temp.
- contaminated bath
    - particles enter through environment
    - machine oil not removed from part
    - maintenance not performed
- incorrect anodization current used
    - wrong calculation used (calculation done for every lot)
    - human error
- incorrect voltage set
    - meter, power supply failure
- broken cable connection during anodize
    - deferred maintenance
    - insufficient tightening of connections
- incorrect anodize timing
    - Timer failure
    - human error
- missing/wrong agitation
    - operator forgot to turn off
    - too much/not enough agitation
- base material
    - out of spec chemically
    - internal stress not to spec
    - grain structure not to spec
    - precipitant structure not to spec
    - wrong base material used
    - visually acceptable material unavailable

FILM UNIFORMITY

Within Wafer Film Uniformity

- **Susceptor Plate Warpage**
  - **heat treatment anneal** TNW
  - assembly TNW
  - swiss cheese flatness TNW
  - as-machined flatness TNW
  - aluminum fluoride growth TNW
  - high temperature creep TNW
- Surface Emissivity
  - base material conditioning (reflectivity) W
  - base material composition W
  - surface roughness (post anodize) W
- Nodule Growth
  - inclusions in base material TNW
  - second phase precipitates in base material TNW
  - voids in base material TNW
- Finger Hole Ridge Formation
  - supplier variability in machining TNW
  - anodize edge defect TNW
  - plasma electrical field TNW
- Center Cap Deformation TMS Only
  - helicoil tang not removed 6" TN
  - gas pocket trapped under center cap
  - heat treat anneal
  - ridge formation
- Anodize Delamination
  - anodize current density TNW
  - variability in base material composition TNW
  - variability in chem prep processing prior to TNW
  - in situ susceptor conditioning history in TNW
  - surface roughening TNW
- Wafer Resting on Lip of Susceptor
  - robot hand-off

Ⓔ

Wafer to Wafer Repeatability (Dep Rate)

- **Monitor Wafer Quality**
  - **wafer backside surface condition** W
- Metrology Capability
  - manufacturers equipment capability vs. customers requirements TNW
- Thermocouple Damage During Assembly
  - twisted during assembly
  - shorted during assembly
  - open during assembly
  - grounded during assembly
- Thermocouple Damage During Installation
  - shorted @ bellows mount TNW
  - open @ bellows mount TNW
  - grounded @ bellows mount TNW
- Thermocouple Calibration
  - incorrect system constants TNW
  - susceptor calibration constant values incorrect TNW
  - susceptor calibration constant values missing TNW
- Thermocouple Offset
  - RF path shifts TNW
  - indeterminant grounding of thermocouple sheath TNW
- Thermocouple Drift
  - thermocouple aging (time based)
- Showerhead TNW
- Net Precursor Delivery
- Blocker Plate

Lot to Lot Repeatability (Dep Rate)

- **Monitor Wafer Quality**
  - **wafer backside surface condition** W
- Metrology Capability
  - manufacturers equipment capability vs. customers requirements TNW
- Thermocouple Damage During Assembly
  - twisted during assembly
  - shorted during assembly
  - open during assembly
  - grounded during assembly
- Thermocouple Damage During Installation
  - shorted @ bellows mount TNW
  - open @ bellows mount TNW
  - grounded @ bellows mount TNW
- Thermocouple Calibration
  - incorrect system constants TNW
  - susceptor calibration constant values incorrect TNW
  - susceptor calibration constant values missing TNW
- Thermocouple Offset
  - RF path shifts TNW
  - indeterminant grounding of thermocouple sheath TN W
- Thermocouple Drift
  - thermocouple aging (time based)
- Showerhead TNW
- Net Precursor Delivery
- Blocker Plate

E Wafer off Center in Susceptor Pocket
  - robot hand-off TNW
- Susceptor Droop TNW
  - creep yield of susceptor support bracket
- Susceptor Spacing Incorrectly Set
  - susceptor alignment (spacing & leveling) TNW
  - incorrect system constants entered TNW
  - incorrect spacing setpoint in recipe TNW
  - susceptor lift opto-flag position has changed TNW
- Susceptor Not Level vs. Showerhead
  - alignment (spacing & leveling) TNW
- Susceptor Offcenter vs. Showerhead
  - alignment (spacing & leveling) TNW
  - lift assembly position shift (accidental rotation) TNW
- Loose Top Plate
  - loose fasteners TNW
  - damaged ceramic TNW
- Loose Support Bracket
  - loose fasteners TNW
  - damaged ceramic TNW
- Total Gas Flow
- Showerhead
- Blocker Plate
- Radiation Source (Lamps)
- Ceramic Web Breakage

Note:
T=TEOS (ILD)
N=Nitride (Passivation)
W=Tungsten
TMS=top mount susceptor

FILM STRESS

WAFER TO WAFER REPEATABILITY

- RF Generator Variability TN
- RF Match Network Variability
- External RF Connections
- Showerhead Coupling
- Susceptor Ground Strap Connection to Chamber Wall
  - loose connection
- Susceptor Ground Strap Fraying TN
  - ground strap rubbing on bellows (cable routing)
  - ground strap too short
- Susceptor Ground Strap Cable Broken
  - poor weld joint
  - excessive ground strap fraying
- Susceptor Ground Boss to Tube Weld TN
  - poor weld joint
- Susceptor Ground Tube to Plate Connection TN
  - loose fasteners
  - fasteners overtightened (threads stripped)
  - incorrect fasteners used
  - stress relaxation of joint
- Susceptor Plate Dielectric Film Variability TN
  - aluminum fluoride film formation rate (within susceptor)
  - aluminum fluoride film formation rate (susceptor to susceptor)
- Susceptor Plate Warpage
  - heat treatment anneal
  - assembly
  - swiss cheese flatness
  - as-machined flatness
  - aluminum fluoride growth rate differential
  - high temperature creep
- Nodule Growth TN
  - inclusions in base material
  - second phase precipitates in base material
  - voids in base material
- Finger Hole Ridge Formation TN
  - supplier variability in machining
  - anodize edge defect phenomenon
  - plasma electrical field effect
- Center Cap Deformation TN
  - helicoil tang not removed
  - gas pocket trapped under center cap
  - heat treat anneal
  - ridge formation

Ⓕ

LOT TO LOT REPEATABILITY

- RF Generator Variability TN
- RF Match Network Variability
- External RF Connections
- Showerhead Coupling
- Susceptor Ground Strap Connection to Chamber Wall
  - loose connection
- Susceptor Ground Strap Fraying TN
  - ground strap rubbing on bellows
  - ground strap too short
- Susceptor Ground Strap Cable Broken
  - poor weld joint
  - excessive ground strap fraying
- Susceptor Ground Boss to Tube Weld TN
  - poor weld joint
- Susceptor Ground Tube to Plate Connection TN
  - loose fasteners
  - fasteners overtightened (threads stripped)
  - incorrect fasteners used
  - stress relaxation of joint
- Susceptor Plate Dielectric Film Variability TN
  - aluminum fluoride film formation rate (within susceptor)
  - aluminum fluoride film formation rate (susceptor to susceptor)
- Susceptor Plate Warpage
  - heat treatment anneal
  - assembly
  - swiss cheese flatness
  - as-machined flatness
  - aluminum fluoride growth rate differential
  - high temperature creep
- Nodule Growth TN
  - inclusions in base material
  - second phase precipitates in base material
  - voids in base material
- Finger Hole Ridge Formation TN
  - supplier variability in machining
  - anodize edge defect phenomenon
  - plasma electrical field effect
- Center Cap Deformation TN
  - helicoil tang not removed
  - gas pocket trapped under center cap
  - heat treat anneal
  - ridge formation

Ⓖ

F Anodize Delamination TN
- anodize current density
- variability in base material composition
- variability in chem prep processing prior to anodize
- in situ susceptor conditioning history in process chbr
- Surface roughening

- Wafer Resting on Lip of Susceptor
  - robot hand-off
- Wafer off Center in Susceptor Pocket TN
  - robot hand-off
- Susceptor Droop
  - creep yield of susceptor support bracket
- Susceptor Spacing Incorrectly Set TN
  - susceptor alignment (spacing & leveling)
  - incorrect system constants entered
  - incorrect spacing setpoint in recipe
  - susceptor lift opto-flag position has changed
- Susceptor Not Level vs. Showerhead TN
  - alignment (spacing & leveling)
- Susceptor Offcenter vs. Showerhead TN
  - alignment (spacing & leveling)
  - lift assembly position shift (accidental rotation)
- Loose Top Plate TN
  - loose fasteners
  - damaged ceramic
- Loose Support Bracket TN
  - loose fasteners
  - damaged ceramic
- Gas Flow Ratios W
- New Susceptor Conditioning N

G Anodize Delamination TN
- anodize current density
- variability in base material composition
- variability in chem prep processing prior to anodize
- in situ susceptor conditioning history in process chbr
- Surface roughening

- Wafer Resting on Lip of Susceptor
  - robot hand-off
- Wafer off Center in Susceptor Pocket TN
  - robot hand-off
- Susceptor Droop
  - creep yield of susceptor support bracket
- Susceptor Spacing Incorrectly Set TN
  - susceptor alignment (spacing & leveling)
  - incorrect system constants entered
  - incorrect spacing setpoint in recipe
  - susceptor lift opto-flag position has changed
- Susceptor Not Level vs. Showerhead TN
  - alignment (spacing & leveling)
- Susceptor Offcenter vs. Showerhead TN
  - alignment (spacing & leveling)
  - lift assembly position shift (accidental rotation)
- Loose Top Plate TN
  - loose fasteners
  - damaged ceramic
- Loose Support Bracket TN
  - loose fasteners
  - damaged ceramic
- Gas Flow Ratios W
- New Susceptor Conditioning N

PARTICLES

- **Anodize Degradation** T,N,W
  - **Gray Grit** T,N
    - **variation in anodize current density**
  - **Zits** W
    - inclusions in base material
    - second phase precipitates in base material
  - Poppy Seed W
    - inclusions in base material
    - second phase precipitates in base material
  - Mudflats W
    - anodize cracking @ crack spacing, (x,y) same & = 1 - 5 mm
    - surface roughening
  - Orange Peel W
    - anodize cracking @ crack spacing,(x,y) delta between 1 -3 , & = 0.1 - 1 mm
    - surface roughening
  - Delamination T,N,W
    - anodize current density
    - variability in base material composition
    - variability in chem prep processing prior to anodize
    - in situ susceptor conditioning history in process chamber
    - surface roughening
  - Bicycle Spoke W
    - anodize cracking @ radial crack spacing originating from center of susceptor
    - surface roughening
  - Nodules W
    - inclusions in base material
    - second phase precipitates in base material
    - voids in base material
  - Chicken Pox W
    - surface contamination

- **Susceptor Surface Contamination** T,N,W
  - **anodize rinse process**
  - **spit**
  - dandruff
  - skin oil
  - perspiration
  - isopropyl alcohol
  - clean room wipes
  - non-cleanroom wipes
  - other miscellaneous contaminants
- Nickel Flaking T,N,W
  - supplier quality
  - hardware damage during installation
  - poor design specification & selection
- Ceramic Shield T,N
- Gas Delivery System T,N,W
- Blocker Plate Residue T
- Showerhead Residue TNW
- Heater Window W
- O-Rings TNW
- Throttle Valve & Foreline Residue TNW
- Pumping Plate TNW
- Slit Valve TNW
- Process Kit Alignment TNW
- Clean Recipe TNW
- Chamber Seasoning TNW
- Chamber Seasoning TNW
- Deposition Process TNW
- Wafer Handling System TNW
- Chamber Cross-Contamination T
- Chamber Cross-Contamination T
- Metrology TNW

OTHER SPECIFIC PROPERTY PARAMETERS

REFRACTIVE INDEX

- **RF Generator Variability** TN
- **RF Match Network Variability** TN
- **External RF Connections** TN
- Showerhead Coupling TN
- G. S. Connect to Chmbr Wall TN
  - loose connection
- Susceptor Ground Strap Fraying TN
  - ground strap rubbing on bellows (cable routing)
  - ground strap too short
- Susceptor G.S. Cable Broken T,N,W
  - poor weld joint
  - excessive ground strap fraying
- Susceptor Ground Boss to Tube W TN
  - poor weld joint
- Susceptor Ground Tube to Plat T,N
  - loose fasteners
  - fasteners overtightened
  - incorrect fasteners used
  - stress relaxation of joint
- Susceptor Plate Dielectric Film Variability
  - aluminum fluoride film formation rate (within susceptor)
  - aluminum fluoride film formation rate (susceptor to susceptor)
- Susceptor Plate Warpage TN
  - heat treatment anneal
  - assembly
  - swiss cheese flatness
  - as-machined flatness
  - aluminum fluoride growth rate
  - high temperature creep
- Nodule Growth TN
  - inclusions in base material
  - precipitates in base mat.
  - voids in base material
- Finger Hole Ridge Formation TN
  - supplier variability in machining
  - anodize edge defect phenomenon
  - plasma electrical field effect
- **Center Cap Deformation** TN
  - **helicoil tang not removed**
  - **gas pocket trapped under center cap**
  - heat treat anneal
  - ridge formation
- Anodize Delamination TN
  - anodize current density
  - variability in base material composition
  - variability in chem prep processing prior to anodize
  - in situ susceptor conditioning history in process chamber
  - surface roughening
- Wafer Resting on Lip of Susceptor
  - robot hand-off
- Wafer off Center in Susceptor Pocket (Combined with Electrode Alignment)
  - robot hand-off
- Susceptor Droop TN
  - creep yield susceptor support bracket
- Susceptor Spacing Incorrectly Set
  - susceptor alignment (spacing & leveling)
  - incorrect system constants entered
  - incorrect spacing setpoint in recipe TN
  - susceptor lift opto-flag position has changed
- Susceptor Not Level vs. Showerhead
  - susceptor alignment (spacing & leveling)
- Susceptor Offcenter vs. Showerhead
  - susceptor alignment (spacing & leveling)
  - lift assembly position shift (accidental rotation)
- Loose Top Plate TN
  - loose fasteners
  - damaged ceramic
- Loose Support Bracket TN
  - loose fasteners
  - damaged ceramic
- Gas Flow Ratios W
- New Susceptor Conditioning N

FILM PEELING WT

- **Wafer Surface Activation**
  - **Backside Etch Set-up** W
    - **incorrect system constants entered**
    - incorrect spacing setpoint in recipe
    - susceptor lift opto-flag position has changed
- Excessive Film Stress WT
  - incorrect gas ratios

WAFER BACKSIDE DEPOSIT

- Backside Etch Set-up
- Backside Purge

Note:
T=TEOS (ILD)
N=Nitride (Passivation)
W=Tungsten
TMS=top mount susceptor

Appendix B

Susceptor Failure Modes and Effects Analysis (FMEA)

Failure Mode	Cause(s)	Occurrence effects	Occurrence failure mode	Occurrence root cause	Occurrence %	Rank	Effects	Yield	Down-time	Severity	Severity * Occurrenc
Anodize Delamination	anodize current density	0.13	0.6	0.25	1.95	7	Particles	6	3	9	60
	variability in base material composition	0.13	0.6	0.25	1.95	7	Particles	6	3	9	60
	* chem prep time	0.13	0.6	0.1	0.78	3	Particles	6	3	9	24
	* wrong/ variable temp bath	0.13	0.6	0.1	0.78	3	Particles	6	3	9	24
	broken connection between susceptors and rack, rack & cable during anodize	0.13	0.6	0.1	0.78	3	Particles	6	3	9	24
	rack and cathode design not optimized	0.13	0.6	0.08	0.62	2	Particles	6	3	9	20
	in situ susceptor conditioning history in process chamber	0.13	0.6	0.05	0.39	1	Particles	6	3	9	12
	*wrong/poor quality supplied chemicals	0.13	0.6	0.04	0.31	1	Particles	6	3	9	10
	missing/wrong agitation	0.13	0.6	0.02	0.16	1	Particles	6	3	9	5
	* concentration impurity in bath	0.13	0.6	0.01	0.08	0	Particles	6	3	9	3
	anodize current density	0.055	0.1	0.25	0.14	1	Uniformity	6	3	9	5
	variability in base material composition	0.055	0.1	0.25	0.14	1	Uniformity	6	3	9	5
	* chem prep time	0.055	0.1	0.1	0.06	0	Uniformity	6	3	9	2
	* wrong/ variable temp bath	0.055	0.1	0.1	0.06	0	Uniformity	6	3	9	2
	broken connection between susceptors and rack, rack & cable during anodize	0.055	0.1	0.1	0.06	0	Uniformity	6	3	9	2
	rack and cathode design not optimized	0.055	0.1	0.08	0.04	0	Uniformity	6	3	9	2
	in situ susceptor conditioning history in process chamber	0.055	0.1	0.05	0.03	0	Uniformity	6	3	9	1
	* wrong/poor quality supplied chemicals	0.055	0.1	0.04	0.02	0	Uniformity	6	3	9	1
	missing/wrong agitation	0.055	0.1	0.02	0.01	0	Uniformity	6	3	9	1
	* concentration impurity in bath	0.055	0.1	0.01	0.01	0	Uniformity	6	3	9	1
Backside Etch Set-up	incorrect spacing setpoint in recipe	0.008	0.33		0	0	Film Peeling	4	3	7	0
	incorrect system constants entered	0.008	0.33		0	0	Film Peeling	4	3	7	0
	susceptor lift opto-flag position has changed	0.008	0.33		0	0	Film Peeling	4	3	7	0

Cracked Ceramic	base material composition wrong	0.008	0.01	0.8	0.01	0	Uniformity	2	3	5	0
	poor machining techniques used	0.008	0.01	0.2	0	0	Uniformity	2	3	5	0
	packaging problems (OEM)	0	0.5	0	0	0	Received at Intel Damaged	2	3	5	0
	packaging problems (subcontractor)	0	0.5	0	0	0	Received at OEM Damaged	2	3	5	0
Excessive Film Stress	incorrect gas ratios	0.008	1		0	0	Film Peeling	4	3	7	0
Finger Hole Ridge Formation	anodize edge defect phenomenon	0.055	0.25	0.6	0.83	3	Uniformity	6	3	9	26
	plasma electrical field effect	0.055	0.25	0.2	0.28	1	Uniformity	6	3	9	9
	supplier variability in machining	0.055	0.25	0.2	0.28	1	Uniformity	6	3	9	9
First Wafer Effect (Chamber Conditioning)		0.13	0		0	0	Particles	6	3	9	0
		0.055	0		0	0	Uniformity	6	3	9	0
Loose Support Bracket	loose fasteners	0.055	0.01	0.9	0.05	0	Uniformity	6	3	9	2
	damaged ceramic	0.055	0.01	0.1	0.01	0	Uniformity	6	3	9	1
Loose Top Plate	damaged ceramic	0.055	0.05	0.5	0.14	1	Uniformity	6	3	9	5
	loose fasteners	0.055	0.05	0.5	0.14	1	Uniformity	6	3	9	5
Manufacturing defects/assembly problems	Cracked Ceramic	0.008	1		0	0	Received at Intel damaged	2	3	5	0
	Thermocouple damage/installation	0.008	1		0	0	Received at Intel damaged	0	3	3	0
	Loose/Missing Fasteners	0.006	1		0	0	Received at Intel damaged	0	1	1	0
Metrology Capability	manufacturers equipment capability vs. customers requirements	0.055	0.01	1	0.06	0	Uniformity	6	3	9	2
Monitor Wafer Quality	wafer backside surface condition	0.055	0.01	1	0.06	0	Uniformity	6	3	9	2
Nickel Flaking	skipped nickel plating step	0.13	0.07	0.5	0.46	2	Particles	6	3	9	14
	poor plating quality	0.13	0.07	0.25	0.23	1	Particles	6	3	9	7
	poor cleaning by original	0.13	0.07	0.1	0.09	0	Particles	6	3	9	3
	wrong chemical composition	0.13	0.07	0.1	0.09	0	Particles	6	3	9	3

	poor design specification & selection	0.13	0.07	0.03	0.03	0	Particles	6	3	9	1
	hardware damage during installation	0.13	0.07	0.02	0.02	0	Particles	6	3	9	1
Nodules (poppy seed, zits, volcanoes)	**second phase precipitates in base material**	**0.13**	**0.3**	**0.75**	**2.93**	**10**	**Particles**	**6**	**3**	**9**	**90**
	inclusions in base material	**0.13**	**0.3**	**0.15**	**0.59**	**2**	**Particles**	**6**	**3**	**9**	**18**
	voids in base material	**0.13**	**0.3**	**0.1**	**0.39**	**1**	**Particles**	**6**	**3**	**9**	**12**
	second phase precipitates in base material	0.055	0.15	0.75	0.62	2	Uniformity	6	3	9	19
	inclusions in base material	0.055	0.15	0.15	0.12	0	Uniformity	6	3	9	4
	voids in base material	0.055	0.15	0.1	0.08	0	Uniformity	6	3	9	3
Surface Emissivity	base material composition	0.055	0.1	0.5	0.28	1	Uniformity	6	3	9	9
	base material conditioning (reflectivity)	0.055	0.1	0.5	0.28	1	Uniformity	6	3	9	9
Susceptor Droop	creep yield of susceptor support bracket	0.055	0.02	1	0.11	0	Uniformity	6	3	9	4
Susceptor Not Level vs. Showerhead	susceptor alignment (spacing & leveling)	0.055	0.01	1	0.06	0	Uniformity	6	3	9	2
Susceptor Offcenter vs. Showerhead	lift assembly position shift (accidental rotation)	0.055	0.01	0.5	0.03	0	Uniformity	6	3	9	1
Susceptor Offcenter vs. Showerhead	susceptor alignment (spacing & leveling)	0.055	0.01	0.5	0.03	0	Uniformity	6	3	9	1
Susceptor Plate Warpage	aluminum fluoride growth rate differential	0.055	0.2	0.17	0.18	1	Uniformity	6	3	9	6
	as-machined flatness	0.055	0.2	0.17	0.18	1	Uniformity	6	3	9	6
	assembly	0.055	0.2	0.17	0.18	1	Uniformity	6	3	9	6
	heat treatment anneal	0.055	0.2	0.17	0.18	1	Uniformity	6	3	9	6
	high temperature creep	0.055	0.2	0.17	0.18	1	Uniformity	6	3	9	6
	swiss cheese flatness	0.055	0.2	0.17	0.18	1	Uniformity	6	3	9	6
Susceptor Spacing Incorrectly Set	incorrect spacing setpoint in recipe	0.055	0.04	0.4	0.09	0	Uniformity	6	3	9	3
	incorrect system constants entered	0.055	0.04	0.4	0.09	0	Uniformity	6	3	9	3
	susceptor alignment (spacing & leveling)	0.055	0.04	0.1	0.02	0	Uniformity	6	3	9	1

	susceptor lift opto-flag position has changed	0.055	0.04	0.1	0.02	0	Uniformity	6	3	9	1
Susceptor Surface Contamination (chicken pox)	anodize rinse process	0.13	0	0	0	0	Particles	6	3	9	0
	clean room wipes	0.13	0	0	0	0	Particles	6	3	9	0
	dandruff	0.13	0	0	0	0	Particles	6	3	9	0
	isopropyl alcohol	0.13	0	0	0	0	Particles	6	3	9	0
	non-cleanroom wipes	0.13	0	0	0	0	Particles	6	3	9	0
	other miscellaneous	0.13	0	0	0	0	Particles	6	3	9	0
	perspiration	0.13	0	0	0	0	Particles	6	3	9	0
	skin oil	0.13	0	0	0	0	Particles	6	3	9	0
	spit	0.13	0	0	0	0	Particles	6	3	9	0
Thermocouple	grounded during assembly	0.055	0.01	0.08	0	0	Uniformity	6	3	9	1
	incorrect system constants	0.055	0.01	0.08	0	0	Uniformity	6	3	9	1
	indeterminate grounding of thermocouple sheath	0.055	0.01	0.08	0	0	Uniformity	6	3	9	1
	RF path shifts	0.055	0.01	0.08	0	0	Uniformity	6	3	9	1
	susceptor calibration constant values missing	0.055	0.01	0.08	0	0	Uniformity	6	3	9	1
	susceptor calibration constant values incorrect	0.055	0.01	0.08	0	0	Uniformity	6	3	9	1
	thermocouple aging (time based)	0.055	0.01	0.08	0	0	Uniformity	6	3	9	1
	thermocouple grounded @ bellows mount during	0.055	0.01	0.08	0	0	Uniformity	6	3	9	1
	thermocouple open @ bellows mount during installation	0.055	0.01	0.08	0	0	Uniformity	6	3	9	1
	thermocouple open during assembly	0.055	0.01	0.08	0	0	Uniformity	6	3	9	1
	thermocouple shorted @ bellows mount during installation	0.055	0.01	0.08	0	0	Uniformity	6	3	9	1
	thermocouple shorted during assembly	0.055	0.01	0.08	0	0	Uniformity	6	3	9	1
	thermocouple twisted during assembly (decalibration)	0.055	0.01	0.08	0	0	Uniformity	6	3	9	1
Wafer off Center in Susceptor Pocket	robot hand-off	0.055	0.02	1	0.11	0	Uniformity	6	3	9	4
Wafer Resting on Lip of Susceptor	robot hand-off	0.055	0.02	1	0.11	0	Uniformity	6	3	9	4

Appendix C

Qualitative Analysis Matrix Ranking Information

Commercial Issues	***Rank***
no proprietary issues	
If a second source is chosen, proprietary agreements will be violated	1
There is a high probability that proprietary agreements will be violated	2
If a second source is chosen, proprietary agreements may be violated	3
There is a low probability that proprietary agreements will be violated	4
No proprietary issues	5
supplier financially viable	
Supplier cannot finance or deliver current reqt's, is candidate for CCA supplier watch list	1
Supplier can finance and deliver some current reqt's, no growth or expansion capability	2
Supplier can finance and deliver current reqt's.	3
Supplier can finance and deliver current reqt's, has capability to become a market revenue leader	4
Supplier is a stable, market revenue leader	5
no maintenance agreement impact	
Maintenance/warranty agreements are fully nullified by this change	1
	2
Maintenance/warranty agreement is at risk with partial impact	3
	4
Maintenance/warranty agreements will remain in place	5
Spare part can be supplied without redesign or mfr. processes modification.	
Supplier must design a custom part and/or modify mfr. processes to fit our needs.	1
Major changes to an existing design and/or mfr. process is required	2
More than one minor change to an existing design and/or mfr. process is required	3
Minor change to an existing design and/or mfr. process is required	4
Part is a standard: No changes in design or manufacturing processes are required.	5
Total cost of ownership reduction (verify with data in financial impact section)	
Cost of ownership will increase 10% or more as a result of implementing this change	1
Cost of ownership increase between 0% and 10% as a result of this change	2
Cost of ownership will not increase or decrease as a result of this change	3
Cost of ownership will decrease between 0% and 10% as a result of this change	4
Cost of ownership will decrease by 10% or more as a result of this change	5
Ease of doing business	
Supplier is unresponsive, inconveniently located, has language barrier	1
Supplier reacts to some requests, marginal support infrastructure	2

Supplier reacts to requests, convenient to some sites, adequate support infrastructure	3
Supplier anticipates some needs, is located at most sites; Infrastructure above avg.	4
Supplier anticipates needs, is located at every site, superior communication capability	5

Past history with Intel

Supplier did not meet performance goals in the past	1
Intel has no history with supplier; performance indicators are average	2
Supplier met performance goals in the past	3
Intel has no history with supplier; performance indicator are above average	4
Supplier exceeded performance goals in the past; or indicators are well above avg.	5

Supplier Capability Issues

Technical design expertise at supplier

Supplier expertise is limited to manufacturing; no design or technical support exists	1
Supplier is beginning to develop design and technical support expertise	2
Supplier demonstrates minimal competance in technical design	3
Supplier has adequate design and technical expertise; is beginning to proactively improve	4
Supplier is a technology market leader	5

Quality system in place at supplier

No formal quality control procedures are in place at the supplier	1
Quality control procedures are in place, no mgmt commitment for improvement	2
Quality control procedures are in place, mgmt committed to improve, good results	3
Quality control procedures reflect customer needs	4
Quality control procedures are systematically implemented to exceed customer expectations	5

Sub-supplier quality system

Sub-supplier performance not monitored	1
Sub-supplier performance is monitored, ineffective actions taken	2
Sub-supplier performance is adequate, requires constant intervention by supplier	3
Sub-supplier base is proactively improving	4
Sub-suppliers are industry leaders in quality systems	5

Production capacity of supplier

Supplier cannot support Intel total volume requirements; cannot / will not expand	1
Supplier cannot support Intel volume requirements, can/will increase capacity	2
Supplier can currently support Intel volume requirements; no surge capacity	3
Supplier can support Intel volume requirements, plus upside	4
Supplier can support Intel upside in addition to other customer requirements	5

Supplier field service capability

No service capability or intention	1
Supplier will need to hire and train field service personnel, have done so in the past	2
Supplier will not need to hire additional support; training is required	3
Supplier can support needs with existing manpower and skill base	4

Supplier forecasts support needs and develops responsive/cost effective solutions	5

Reliability systems maturity

No customer input; no Q&R expertise;no multifunctional teams; functional testing only	1
Satisfies min requirements; statistical methods used as required;some debugging testing done	2
Customer inputs taken; some Q&R expertise; modeling reliability; subsys. tests done	3
Seeks customer inputs;structured,multi-functional design process;statistical methods used routinely	4
Customer / Q&R fully integrated; Reliability is managed, not reacted to	5

Change Control Issues

No Safety/Ergonomic risk

Significant safety / ergonomic risk	1
Some safety / ergonomic risk	2
Safety / Ergonomic ease not affected by this change	3
Safety / Ergonomic ease is improved with this change	4
Safety / Ergonomic ease significantly improved with this change	5

Compatibility with existing equipment design

Significant equipment modifications are necessary to accept new spare part	1
Significant equipment mods may be necessary; testing needed to determine extent	2
Some equipment modifications may be necessary to accept new spare part	3
Minor equipment mods may be necessary; testing needed to determine extent	4
Spare part is completely compatible with existing equipment	5

No impact on process synergy

This change cannot be made at all fabs, violates copy exactly	1
	2
This change cannot be made at all fabs, but will not affect process results	3
	4
All fabs can and are willing to implement this change	5

No negative impact to process step or other system components

Process/component(s) will be affected, modification required	1
Process /components(s) will be affected, extensive testing required	2
Process /component(s) will be affected, minor testing will be required	3
Some risk that process /component(s) will be affected, tests will eliminate risk	4
Low risk of process/component impact	5
No risk that process/component(s) will be affected by this change	6

No negative impact to previous / subsequent processes or components

Other process(es)/component(s) will be affected, modification required	1
Other process(es)/components(s) will be affected, extensive testing required	2
Other process(es)/component(s) will be affected, minor testing will be required	3
Some risk that other process(es)/component(s) will be affected, tests will eliminate risk	4
Low risk of other process/component impact	5

No risk that other process(es)/component(s) will be affected by this change	6
No Intel customer notification necessary	
Change will need to be approved by Intel's customers before it can be implemented	1
Change will need to be communicated to Intel's customers before implementation	3
No change notification to customer required	5