Quantifying the Source of Reentrant Line Variability and the Effects of Processes Standardization on Tool Availability Variability

by

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Bachelor of Science in Civil and Environmental Engineering, University of Vermont (2002)

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Master of Business Administration

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Abstract

This thesis quantifies the sensitivity of tool availability variability with respect to product throughput and examines how Intel’s High Precision Maintenance initiative can be used to minimize these effects. Tools with variable availability release spikes of material into a route which can cause downstream areas to experience irregular queues. The reentrant multi-product loops typical to Intel’s manufacturing processes can make it difficult to identify the source of long queues. The variability analysis, developed during the internship uses D2 facility availability and cycle time data to generate a variability correlation, called TAC-TOOT which identifies tools within the facility contributing to throughput time.

The High Precision Maintenance initiative is an Intel developed program which focuses on the standardization of maintenance processes. The success of the High Precision Maintenance initiative is closely linked to the ability of factory management to motivate equipment technicians. The thesis examines a number of tools with highly variable availability, the effects of the high precision initiative on variability and levers factory management can use to motivate technicians.

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Chapter 1: Introduction

1.1 Overview

The key challenge for Intel is moving product quickly to the global semiconductor market. Intel depends on the operating efficiency and capacity of its factories to give it the agility to respond to fluctuating market demand. Semiconductor factories face unique layout challenges because the flow of material though the manufacturing line is reentrant. Reentrant flow is material that is processed by the same sequence of tools repeatedly. A small increase in tool process time is magnified in wafer throughput time since the wafer is processed by the tool multiple times.

Intel’s Factories use an Automated Material Handling System (AMHS) to move wafers quickly through the nonlinear reentrant process flow. The AMHS can move wafers between tools at opposite ends of the factory with minimal affects to wafer travel time. Additionally the AMHS handles the storage of work in progress (WIP) when tools are unavailable to process it. Automated WIP movement and storage increases factory utilization but removes many of the visual indicators associated with large volumes of WIP.

These visual indicators allow factory management to understand how well the line is operating by looking at the distribution of WIP across the factory floor. When WIP collects in one area, it is simple for factory management to see that there is an issue with one of the tools on the line. In the case of Intel, because material is transported by the AMHS and routed in reentrant flow it is difficult to understand where large volumes of WIP were generated and how they impact the throughput of the factory.
1.2 Problem Statement

This thesis focuses on identifying tools which affect the cycle time of downstream processes and using the High Precision Maintenance program to mitigate these effects. Tools which affect the cycle time of downstream processes typically have high capacity and variable availability. Such tools are frequently down but their high capacity allows them to quickly process any built up WIP. This releases a WIP bubble into the line which moves through the following process steps until it reaches a tool with lower capacity than the original tool. The lower capacity tool cannot process the material as fast as it arrives and a queue begins to accumulate. Cycles such as this one have serious impact on wafer throughput because WIP passes through both queues multiple times in reentrant process flow.

Intel has developed excellent online WIP monitoring systems which give management the ability to observe WIP volumes at individual tool locations. While it is important to understand where WIP is accumulating, it is even more important to understand what is causing these elevated levels of WIP. This thesis develops a variability analysis, called TAC-TOOT which identifies tools which repeatedly generate WIP bubbles affecting the cycle time of downstream operations.

The High Precision Maintenance (HPM) initiative is a program Intel created to minimize availability variability by standardizing tool preventative maintenance. The initiative, similar to the Toyota Production Method uses the concept that tool preventative maintenance should be treated the same way pit crews on Formula 1 race cars approach pit stops. The crew should be completely prepared with tools and parts in place prior to the equipment being taken down. Once the tool is taken down, the maintenance processes is standardized so that its success is completely independent of the equipment technician. This thesis evaluates the success of Intel’s HPM program.

1.3 Approach

Research for this thesis begins with the evaluation of the HPM effort at the D2 Fab which was started a few months before research commenced. During the first month of
research, a new experimental preventive maintenance team in Area C was formed. In addition, equipment engineers in Area C also begin drastically reducing the frequency at which preventive maintenance is performed. Both efforts have significant effects on the area’s availability but it is difficult to separate the contributions of each effort. The TAC-TOOT analysis is developed to help the preventative maintenance team understand how the variability in Area C affected cycle times in downstream areas. The use of the TAC-TOOT analysis is further expanded to help factory management identify other areas which are affecting the downstream cycle times of other processes.

1.4 Outline of Thesis

Chapter 2 begins by describing Intel and a brief history of the location where the research was performed, the D2 Factory. Chapter 3 describes the queuing theory behind the importance of availability variability reductions and the approaches Intel has taken to identify tools which create variability. Chapter 4 introduces the TAC-TOOT analysis and presents a semiconductor simulation model which shows why it is important to use the variability metric rather than the average metric to identify tools which are affecting the cycle time of downstream tools. Chapter 5 describes the structure and implementation of the High Precision Maintenance initiative. Chapter 6 discusses how the preventative maintenance team in Area C used the HPM initiative’s 8 key attributes to help it succeed in reducing variability. The last chapter reviews important observations made in the previous chapters and makes recommendations which would improve the effectiveness of the High Precision Analysis.
Chapter 2: Intel Background

2.1 Intel

Intel Corporation, an innovator in the silicon industry for over 35 years was founded in 1968 by Bob Noyce and Gordon Moore. With just under 100,000 employees and over 3.8 billion dollars in revenues, the corporation is the world's largest chip producer. The industry, in response to increased competition and reduced growth over the past few years has focused significant efforts on streamlining manufacturing processes. Intel has created a number of successful corporate initiatives targeting lean manufacturing.

2.2 D2 Factory

D2, located in Santa Clara next to Intel’s headquarters was the company’s first 200mm semiconductor factory. It operates both as a production and development facility. While it has been rumored that Intel may shut down this facility as a result of the high Silicon Valley operating costs, no steps have been taken to support this theory. Nonetheless, the topic has motivated both D2 technicians and management to move D2 towards greater profitability.

The age and location of D2 has forced management to face a number of challenges which younger factories located in low cost areas have not encountered. Some of these issues include high cost of labor, aging workforce and factory configuration. Over the past two decades, Silicon Valley has become one of the most expensive locations to operate a factory. The cost of the technical labor which operates the facility is significant and the high demand for experienced technicians in Silicon Valley exacerbates the issue. Additionally, because D2 is one of the oldest operating semiconductor factories the workforce is very senior. The semiconductor industry is still relatively young so the issues surrounding a senior workforce do not revolve around age or retirement but align more closely with motivating a workforce that is at the top of its salary bracket. The D2
management has done an excellent job of managing the expectations of technicians without the ability to use financial incentives.

The age of the factory plays a significant role in its ability to achieve high volume production. The limiting factors are the floor space and the disproportional division of areas to the number of tools in various clusters. This forces the factory to have an unusual configuration often prohibiting tool groups from being co-located. The division of tool groups throughout the factory causes issues for efficient WIP routing and technician allocation.
Chapter 3: Variability and Semiconductor Throughput

This chapter describes the queuing theory behind why variability has such significant effects on WIP and Intel’s previous efforts to identify tools which cause variability. The P-K formula developed by Pollaczek and Khintchine independently in the 1930’s uses queuing theory to explain how variable arrival rates affect WIP. While Intel understands the adverse roll which variability plays in affecting factory WIP, it was not until the late 90’s that the company developed the A80 metric to identify tools with highly variable availability. While the A80 metric is an excellent tool for understanding individual tool variability, Allen and Capellen developed a model which identifies tools with variable availability which affected the cycle time of other tools. Their paper, Improving output capability through minimizing variability in an HVM fab proposes a model which uses 3 measures of variability, availability, cycle time and outs, to identify highly variable tools affecting the throughput of other areas.

3.1 Pollaczek – Khintchine Formula

The Pollaczek - Khintchine formula, also referenced as the P-K formula, is commonly used to explain the motivation behind variability reduction efforts in semiconductor factories. The formula describes the average WIP in a queue for a process where the arrival rate is highly variable and the process time is relatively stable (M/G/1). Previous research suggests that arrival rates in semiconductor factories resemble an exponential distribution. The P-K formula is shown below

---

1 Heyde, et al., Statisticians of the Centuries (New York : Springer, 2001) 430
3 Allen and Capellen, “Improving output capability through minimizing variability in an HVM fab” (IMEC, 2005)
4 Heyde, et al., Statisticians of the Centuries, 2001 p430
WIP = {\rho} + \{[\rho^2/(2*(1 - \rho))]\} + \{[\lambda^2*\sigma^2]/[2*(1 - \rho)]\}

WIP = average number in queue and in process (units)
\lambda = arrival rate (units per hour)
\mu = service rate (units per hour)
\rho = \lambda / \mu (traffic intensity or utilization)
\sigma^2 = variance of service time distribution (0 for constant service times)

The formula can be broken into three segments; tool utilization, effects of increased tool utilization and arrival variability. The contribution of tool utilization to the average WIP in the queue is large which is why many factories load their tools well below capacity. As tool utilization approaches 100 percent, the denominator of the formula’s second and third segments approaches zero driving the WIP towards infinity.

Figure 1 Effects of utilization and arrival rate variability on WIP\(^5\)

Additionally, the effects of highly variable arrival rates play a significant role in the average WIP in a queue. The numerator of the formula’s third segment describes how variability is incorporated into the calculation of average WIP. Often semiconductor factories choose to reduce WIP by focusing on reducing variability as opposed to

increasing capacity. The reduction of arrival rate variability is a change in mindset which costs a fraction of the price of buying additional tools to increase overall capacity.

The relationship between WIP, utilization and arrival rate variability is described in figure 1. Reductions in utilization (traffic intensity) through either reduced wafer releases or increase capacity clearly drives the relationship when capacity is less than 80% utilized. When capacity utilization is greater than 80% arrival rate variability significantly affects WIP in the process.

3.2 A80 Metric

The A80 metric, first piloted in fab A and later adopted by all 200mm factories is the 80 percent confidence interval of a tool’s availability. The measure was adopted because the average availability, denoting the 50% confidence interval was only accurate 50% of the time that WIP was present at the tool while the A80 measure was accurate 80% of the time WIP was present at the tool.

The theory behind choosing an 80 percent confidence interval is described by Cunningham and Babikian in their paper A80-a new perspective on predictable factory performance. The paper explains that theoretically assuming a normal distribution using one standard deviation as the lower bound would lead to an 86% confidence interval. A more robust statistical method would be to use the lower quartile of 25% as the lower end of a confidence interval. Since the availability distribution varies between a Poisson and normal distribution, Cunningham and Babikian choose to use 80% because it was in between 86% and 75%.

D2 is concerned that the A80 is not the appropriate metric to be used by a development factory. This concern is based on the fact that D2 tools spend a significant amount of their time not available to production because they are being used for development

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operations. The method used to calculate A80 measures tools which are not in production as in repair when in D2 often they are being used for development. Measuring a tool’s availability using the time it is available for production in a development factory is a false representation of the time the tool is actually available to process WIP and significantly lowers its A80 metric.

3.3 Intel White Paper – Improving output capability through minimizing variability

The paper, *Improving Output Capability Through Minimizing Variability in an HVM Fab* written by David E. Allen and Rachelle Capellen describes how Intel Fab B maximized its output capacity by minimizing line variability. The factory used a combination of tool cycle time, outs and availability variability to identify tools generating line variability. Cross functional focus teams were then assigned to work with the tool’s equipment engineers and technicians to minimize availability variability.

The holistic method which the factory uses to identify tools generating variability takes into account both the individual tool’s ability to processes WIP on a continuous basis and the effects of upstream processes on the flow of WIP to the tool. The method evaluates three metrics, the availability variability, the outs variability and the cycle time variability. High availability variability is a key indicator that equipment technicians are having trouble keeping the tool up and running. A tool’s outs variability describes the area’s burst capacity. Burst capacity is the ability of a tool to processes high volumes of WIP in short periods of time. A tool’s burst capacity can be used to determine if WIP bubbles created in upstream are being passed through the tool and affecting processes further down stream. The cycle time variability describes the variation in the time between when the WIP arrives at the tool and when the process has been completed. Cycle time variability can indicate either that the area is prone to WIP bubbles created by upstream processes or that the variable availability is hindering the area’s ability to processes WIP.

Allen and Capellen, “Improving output capability through minimizing variability in an HVM fab” (IMEC, 2005)
3.4 Allen & Capellen Variability Model

Allen and Capellen used a unique method to measure variability for cycle time, outs and availability. The formulas below describe how each variability metric is calculated.

a. Cycle Time Variability
Cycle Time Var. = (80\textsuperscript{th} percentile CT − 50\textsuperscript{th} percentile CT) / (50\textsuperscript{th} percentile CT)
High variability ≥ 15%

b. Outs Time Variability
Outs Var. = (50\textsuperscript{th} percentile outs − 20\textsuperscript{th} percentile outs) / (50\textsuperscript{th} percentile outs)
High variability ≥ 15%

c. Availability Variability
Avail. Var. = (50\textsuperscript{th} percentile avail. var. − 20\textsuperscript{th} percentile avail. var.) / (50\textsuperscript{th} percentile Avail. Var.)
High variability ≥ 50%

The reasoning behind the percentile ranges and high variability indicators is not included in the white paper.\(^9\)

**Figure 2 Variability Example\(^{10}\)**

<table>
<thead>
<tr>
<th>Area</th>
<th>Tool</th>
<th>Cycle Time variability</th>
<th>Outs variability</th>
<th>Availability variability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A</td>
<td>49.1%</td>
<td>6.7%</td>
<td>7.9%</td>
</tr>
<tr>
<td>2</td>
<td>B</td>
<td>39.6%</td>
<td>5.4%</td>
<td>7.6%</td>
</tr>
<tr>
<td>2</td>
<td>C</td>
<td>23.1%</td>
<td>13.4%</td>
<td>37.1%</td>
</tr>
<tr>
<td>2</td>
<td>D</td>
<td>43.5%</td>
<td>23.1%</td>
<td>8.8%</td>
</tr>
<tr>
<td>2</td>
<td>E</td>
<td>83.0%</td>
<td>26.0%</td>
<td>16.4%</td>
</tr>
<tr>
<td>3</td>
<td>F</td>
<td>109.3%</td>
<td>17.6%</td>
<td>16.6%</td>
</tr>
<tr>
<td>4</td>
<td>G</td>
<td>148.7%</td>
<td>8.9%</td>
<td>5.6%</td>
</tr>
<tr>
<td>5</td>
<td>H</td>
<td>40.4%</td>
<td>7.7%</td>
<td>4.6%</td>
</tr>
<tr>
<td>5</td>
<td>I</td>
<td>19.0%</td>
<td>8.2%</td>
<td>1.3%</td>
</tr>
</tbody>
</table>

\(^9\) Allen and Capellen, “Improving output capability through minimizing variability in an HVM fab” (IMEC, 2005)
\(^{10}\) Allen and Capellen, “Improving output capability through minimizing variability in an HVM fab” (IMEC, 2005)
Figure 2, provided by Allen & Capellen demonstrates how Intel Fab B used their variability analysis to identify tools which affect the cycle time of steps down stream. In figure 2, tool C with 37.1% availability variability is flagged as having high availability variability. The influxes of WIP that are being created by tool C are not affecting the cycle time of Tool D as a result of its large burst capacity. Burst capacity can be identified through the outs variability. Tools with high outs variability are capable of processing large amounts of WIP and thus have high burst capacity. Additionally, Allen & Capellen propose that Tool D’s high burst capacity adds to the variability created by tool C because of it’s ability to processes WIP so quickly. Tools E, F and G have constrained capacity with low burst capacity and can not handle the variability arrival of WIP which is why the cycle times, 83.0%, 109.3%, and 148.7% are highly variable.

3.5 Conclusion

Intel has understood for over two decades that tool availability variability affects the throughput time of WIP. The P-K formula, developed in the 1930’s is commonly used to explain the theory behind how variability affects throughput. One of the first metrics proposed at Intel to identify tool creating variability was the A80 metric. A80 is calculated for every tool and describes the 80% confidence interval which the tool will be available to processes WIP. While this is an excellent metric for production factories, it does not accurately describe development factory tools because the metric does not account for time tools are taken out of production for development activities. In 2004, a new model to identify availability variability was pioneered by Allen and Capellen at Intel Fab B. The method used the variability of cycle time, outs and available to identify tools generating variability. Intel Fab B used the analysis to identify areas where focus teams would work with equipment engineers and technicians to minimize variability.
Chapter 4: The TAC-TOOT Variability Analysis

Fab D2 is implementing a variability analysis, TAC-TOOT which identifies highly variable tools which affect the cycle time of other tools. TAC-TOOT, an acronym for Tools Affecting Cycle Time Of Other Tools is based on a throughput reduction analysis performed at Intel Fab B described by Allen & Capellan\textsuperscript{11}. D2 has deviated from Intel Fab B’s analysis by refining the variability calculation and developing a method which automates the identification of areas which are the source of high variability. Automation of the variability analysis will allow other factories to easily implement a TAC-TOOT analysis and be able to redistribute the man hours that have in the past been utilised to identify variability towards the reduction of variability.

4.1 Variability Calculation Explanation

The variability metric calculation has been changed from Intel Fab B’s normalized percentile range to an innerquartile range. The innerquartile range is a significantly more robust measure because it includes the primary range of data points and excludes outliers. The following sections describe the specific methodology of the variability calculation for cycle time and availability. The TAC-TOOT analysis does not use outs variability as a component to identify tools creating disruptive variability. Since it is not considered a key indicator, the outs variability metric will not be further analyzed.

Cycle Time Variability

Cycle time is the change in time when material is delivered to a tool to when it leaves the tool. In the case of Intel, cycle time can be explained as the time when a lot arrives at a stocker where material is stored in a queue before processing until the time when the lot exits the tool after processing. The distribution of the cycle times for all tools is skewed

\textsuperscript{11} Allen and Capellen, “Improving output capability through minimizing variability in an HVM fab” (IMEC, 2005)
to the right and bounded by zero. Appendix B shows 14 day cycle time distributions of 35 randomly selected tools within D2.

D2 considered normalizing cycle time variability but found that normalizing variability would draw incorrect assumptions about the relationship between process time and down time. Normalizing the variability removes the scale component from a data set. Removing the scale component assumes that as process time increases so will the variability of cycle time.

**Figure 3 Relationship of cycle time variability with processes time.**

![Cycle Time Variability v. Process Time](image)

Take for instance two tools. Tool A has a process time of 20 minutes with a cycle time variability of 5 minutes. Tool B has a process time of 100 minutes with a cycle time variability of 20 minutes. If the cycle times of the two tools were normalized with their average process time, they would both have the same cycle time variability rank of 0.2. While both tools do have the same cycle time variability to process time ratio, Tool B’s 20 minute variability affects the total WIP process time 400% more than Tool A. The only reason that might validate normalizing the cycle time data set by average process
time would be if the two were correlated. Figure 3 is a graph of the correlation between processes time and cycle time. The correlation coefficient is 0.31 which indicates that the two data sets are very weakly correlated and should not be normalised.

**Availability Variability**

Availability, calculated as a daily percent is the time that a tool is available to processes WIP. The distribution of the availability is skewed to the left and bounded by 100%. The variation is calculated using the innerquartile range. Appendix D shows 14 day cycle time distributions of 11 randomly selected tools at D2. It was determined that normalizing the availability innerquartile range because it was already a percentage did not contribute to the availability variability calculation.

**4.2 TAC-TOOT Analysis Explanation**

The automation of the variability analysis is important because it will allow the analysis to be performed more frequently aligning it closely with changes in tool set management. The analysis correlates tool availability variability with the cycle time variability of downstream processes. It is important to note that this analysis only identifies tools which create variability affecting the cycle time of WIP in downstream operations. The analysis does not identify tools creating variability which only affects the cycle time of their own process. While it is important to identify all tools creating variability, tools creating variability which affects other operations have much larger impacts on overall wafer throughput.

**Semiconductor Fab Promodel Simulation**

A simulation of a semiconductor manufacturing sequence was analysed to show how tool availability affects the cycle time of downstream tools. The model is shown in figure 4. All the tools have a 7 minute process time except for the implant tool which has an 8 minute process time. The litho process is modeled to have a normally distributed down time averaging 10 minutes per hour. The down time standard deviation is adjusted
to show how its variability affects the throughput of the entire line. The litho process availability is calculated as the percentage of time the tool is not available to process WIP. The table shows that as tool availability variability increases the cycle time of the total 6 step sequence also increases.

The relationship between the litho tool availability and the implant tool cycle time is shown in figure 4. The relationship between the average availability and average cycle time has shallow slope while the relationship between the availability variability and cycle time variability has a much steeper slope indicating that they are closely correlated. It is this strong correlation the makes the TAC-TOOT analysis very robust.

Figure 4 Linear Process Example

<table>
<thead>
<tr>
<th>Litho Down Time STD, min/hr, Normal Dist. (Avg = 10min)</th>
<th>Thin Film Cycle time, min</th>
<th>Planar Cycle Time, min</th>
<th>Litho Cycle Time, min</th>
<th>Etch Cycle Time, min</th>
<th>Implant Cycle Time, min</th>
<th>Diffusion Cycle Time, min</th>
<th>Litho Tool Availability</th>
<th>Line Throughput Cycle Time, min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg Down Time = 0</td>
<td>Avg. 7 0</td>
<td>Avg. 7 0</td>
<td>Avg. 7 0</td>
<td>Avg. 7 0</td>
<td>Avg. 8 0</td>
<td>Avg. 7 0</td>
<td>0% 100%</td>
<td>43.0 0</td>
</tr>
<tr>
<td>0</td>
<td>7 0</td>
<td>7 0</td>
<td>7 0</td>
<td>7 0</td>
<td>8 0</td>
<td>7 0</td>
<td>83% 0%</td>
<td>45.7 5.0</td>
</tr>
<tr>
<td>5</td>
<td>7 0</td>
<td>7 0</td>
<td>7 0</td>
<td>7 0</td>
<td>8.6 1.6</td>
<td>7 0</td>
<td>84% 11%</td>
<td>46.3 5.6</td>
</tr>
<tr>
<td>10</td>
<td>7 0</td>
<td>7 0</td>
<td>7 0</td>
<td>7 0</td>
<td>9.4 2.1</td>
<td>7 0</td>
<td>83% 23%</td>
<td>49.1 10.9</td>
</tr>
<tr>
<td>15</td>
<td>7 0</td>
<td>7 0</td>
<td>7 0</td>
<td>7 0</td>
<td>10.2 4.0</td>
<td>7 0</td>
<td>81% 30%</td>
<td>55.2 19.3</td>
</tr>
<tr>
<td>20</td>
<td>7 0</td>
<td>7 0</td>
<td>7 0</td>
<td>7 0</td>
<td>11.6 5.1</td>
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</tr>
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Assumptions
1. Cycle time is the total time the material spends at the tool. This is the sum of the time WIP waits for the tool and the process time
2. Var. = Variability calculated as the innerquartile range
3. Wafer starts (or Arrival rate to thin films) is 1 wafer per 10 minutes
Spearman Correlation

The correlation calculation which the TAC-TOOT analysis uses to identify the relationship between the availability variability and cycle time variability is the Spearman correlation. The Spearman correlation is a non-parametric measure of correlation which does not require any assumptions about the relationship between the variables\(^\text{12}\).

\[
\rho = 1 - \frac{6 \sum d_i^2}{n(n^2 - 1)}
\]

Where:
\[\rho = \text{Spearman correlation coefficient}\]
\[d_i = \text{Difference between rank order of corresponding values of } x \text{ and } y\]
\[n = \text{number of pairs of values}\]

It is important that the relationship calculation not rely on a frequency distribution since the correlation is drawn from only 6 variability data points. Each variability data point is

a compilation of 2 weeks of daily averages. The analysis examines 12 weeks of historical daily availability and cycle time averages.

**Spreadsheet Analysis**

An excerpt from the spreadsheet variability analysis performed at D2 is shown in figure 5. The operations have been changed to protect Intel confidential line route information. The process step number and area associated with each Spearman coefficient have been listed on the left. Each availability variability data set was correlated with the following ten cell numbers. Each row in the table explains how the availability variability of a process is correlated to the following ten cells including its own.

For example, cell f211 is the Spearman coefficient between cell 211 diffusion and cell 216 implant. To identify which following cycle time operation the Spearman coefficient is evaluating, count out the number of cells it is from the initial cell in the row. In the case of cell f211, it is 6 cells from the initial Spearman coefficient cell. To identify which process cycle times are being correlated, count 6 cells down from cell 211, counting cell 211 as number 1. The result is cell 216 implant.

The analysis spreadsheet highlights two important indicators; tools which affect multiple tools downstream and tools which are affected by multiple upstream tools. The first indicator, tools which affect multiple downstream operations can be best shown with an example using figure 5. The highlighted cells in row 215 etch indicate that the data set of availability variability for 215 etch is correlated with cycle time variability of operations 217 implant, 218 implant, 219 implant and 220 etch. Since 217 implant, 218 implant and 219 implant are all process step 5 performed by different tools, they should be considered the same operation. Thus the variability created by 215 etch is affecting both implant process step 5 and etch process step 6.
It is not clear why 216 implant is the only tool in process step 5 that was not affected by the variability created in 215 etch. One possible explanation is that all tools are not used equally for all process steps. Semiconductor manufacturing is a reentrant process which means that all of the tools are used for multiple processes steps during manufacturing.

The implant area could be configured so that the tool identified in this table as 216 implant is used primarily for another process step and not process step 5.

The second indicator, tools which are affected by multiple upstream tools is important to identify because it shows vulnerability in the line design. An example of this is shown in figure 5. The cycle time variability of tools 217 implant and 218 implant in process step 5 exhibit a correlation between the availability variability of 209 diffusion, 213 etch and
215 etch. The probability of tools affected by multiple upstream operations to experience increased cycle times as a result of WIP bubbles moving through the area is much higher because there are multiple areas which can cause these WIP bubbles. While it is important to pursue the standardization of areas which are creating these WIP bubbles, in situations such as these, quicker results might be achieved by increasing the capacity of the affected tool.

4.3 Conclusion
The TAC-TOOT analysis identifies tools with highly variable availability that affects the cycle time of downstream operations. The analysis uses the Spearman coefficient to identify correlations in the previous 12 weeks of availability and cycle time data. Tools with high spearman coefficients can be targeted as having variable availability affecting the cycle time of downstream operations. A Promodel simulation was generated to demonstrate how availability variability affects the cycle time of downstream operations in a controlled environment. The analysis shows that slight increases in variability significantly affect the cycle time of downstream operations.
Chapter 5: High Precision Maintenance

The High Precision Maintenance initiative aims at bringing Intel’s manufacturing division to “The Best Maintenance Organization” by the end of 2008. The program focuses on the improvement of preventative maintenance through standardization, continuous improvement and organizational accountability. By minimizing the variability of tool down time, Intel will be able to reduce process cycle times not only in the target tool but also in other downstream tools. The benefits of the HPM initiative include increased line throughput and decreased factory WIP.

5.1 Formula 1 Pit Crews

HPM associates its equipment maintenance teams with Formula 1 pit crews. Although semiconductor tools do not emulate prestigious Formula 1 race cars, the pit crew’s values are similar to those of the HPM initiative. Pit crews are evaluated on the time the car is in the pit for routine race maintenance just as Intel’s maintenance teams are evaluated on the time a tool is down for preventative maintenance. The pit crew prepares itself before the car arrives similarly to how the maintenance teams should before taking a tool into maintenance. Below is a list of the key attributes which the HPM initiative focuses on;

1. Organizational Commitment and Accountability
   Managers measure, ask about and value maintenance excellence. HPM is engrained in business process and an individual equipment maintenance performance feedback system is in place.

2. Training and Education
   All employees are trained on relative HPM methods, tools and processes.

3. Standardization
Maintenance performance precision is emphasized across all shifts. PM activities are performed using an identical agreed upon method and sequence.

4. **Methodology for Workplace Organization**
   
   Everything has a place and everything is in its place.

5. **Clean and Defect Free**
   
   Tools are kept in like-new conditions.

6. **PM Execution Methodology**
   
   After a tool is brought into operation, it is not taken out of production until the next scheduled PM.

7. **Data System**
   
   Clear indicators are defined, easy to retrieve and tracked by all stakeholders. Data is valued and drives continuous improvement.

8. **Continuous Improvement**
   
   All failures are addressed with a countermeasure and root cause analysis.

5.2 **Online Tools**

Intel corporate has designed a number of online web tools which support the HPM initiative. This section briefly discusses two of the tools which were particularly helpful for D2.

**Fuzion’s PMOS**

The PMOS web application provides an online forum for equipment groups to store information about PM activities. It provides technicians the ability to create preflight checklist templates, use them during individual PM activities and store comments about
the PM for later use. The most valuable portion of this application is the checklist templates. A checklist template is a list of tools and parts required before a PM is begun. These centralized checklists which all technicians agree upon and can edit are a great improvement.

One area where this program could be improved is if it were linked to the online specifications. Currently if an equipment engineer changes a PM activity, an equipment technician must also update the PMOS checklist. By tying the two documents together, this would allow changes in the specifications to seamlessly change the preflight checklist as well.

**Tool Scheduling System**

The Tool Scheduling System (TSS) was created to help bring transparency to tool scheduled and unscheduled downtime. The online program gives individuals in all areas of the factory the ability to see the current and future availability of all tools on the floor. TSS can be programmed with tool preventative maintenance schedules in addition to unique downtime upgrades or repairs.

Rebecca Fearing in her 2004 Thesis, *Managing Preventative Maintenance Activities at Intel Corporation* discusses the benefits of strengthening communications across different functional areas by synchronizing preventative maintenance activities. She explains that starting three preventative maintenance activities simultaneously as opposed to sequentially can reduce WIP waiting time by 50%.

**5.2 Implementation Model at D2**

D2’s implementation model for the HPM initiative follows Intel’s standard process for program rollouts. Two key senior managers are assigned the responsibility of disseminating the initiative through the factory. In the case of the HPM initiative at D2,

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these key roles were assigned to two shift managers on alternating day and night shifts who had over 20 years of experience at Intel. These managers identify equipment engineers and shift managers from each area to implement the HPM initiative. On going HPM methodology training sessions are held for the engineers, shift managers and technicians.

In some areas, Preventative Maintenance (PM) Teams were created. The purpose of these teams was to create focus groups that used the HPM methodology to improve tool preventive maintenance quality. These teams typically consisted of a rotating group of equipment technicians that operated 24 hours for a portion of the work week.

5.3 HPM Organizational Structure
The HPM initiative is structured to interact and leverage many different groups including software developers, factories and strategic objectives. The core group which represents the corporate initiative links these areas together by organizing cross functional meetings. Figure 6 shows the HPM initiative structure.

Figure 6 HPM Initiative Structure
5.4 Conclusion

The HPM initiative, designed to minimize variability in tool PM activities, uses 8 key attributes to drive standardization. The program motivates technicians by drawing on their outside interests through the association of PM teams with Formula 1 pit crews. The initiative was rolled out by longtime shift managers who drove the training and creation of area teams.
Chapter 6: Preventative Maintenance Team

The Preventative Maintenance (PM) team is a unique group created at D2 to perform preventative maintenance activities. Initially the team was created as a solution to skilled equipment technicians shortages. When the team began taking ownership of PM activities, it became clear that it could add significant value to the HPM effort. The following sections describe the PM team’s organization and structure as well as challenges it faced.

6.1 Team Organization and Accountability

The PM team schedule is strategically organized to improve communication between the front end shifts, back end shifts and engineering. Operating 24 hours alternating 3 and 4 days, the shift week starts on Tuesday. Tuesday is half way through the week for the front end shift and near the beginning of the equipment engineer’s standard Monday through Friday work week. The PM team’s week ends on Thursday and alternating Fridays which is halfway through the back end shift’s work week. Figure 7 shows how the shifts operate over a two week cycle.

Figure 7 D2 Work Schedule

At the end of each week, the PM team meets with one member of the area management and equipment engineers to discuss the previous week’s successes, the following week’s
schedule and changes to PM’s which could improve standardization. The commitment from factory management to support the PM team and hold it accountable for the area’s preventative maintenance will be a key driver in the success of the PM team.

6.2 Flexibility
The diversity of tool knowledge on the PM team gives it the ability to make informed decisions concerning tools across the entire area. The PM team consists of five equipment technicians and one equipment engineer. Two of the equipment technicians work on the night shift, two on day and one trainee that swings between shifts. The equipment technicians on each shift are skilled on a variety of tools which allows the team to have 100% utilization.

In the past, skilled equipment technicians were spread over the entire week. Technicians had to be careful not to start a PM on a shift when there wouldn’t be a capable technicians on the alternating shift to continue PM work. Sometime it was just not possible to hold a PM till there was a proper spread of technicians across the 24 hour shift and the tool would sit down for the 12 hour shift when no one was able to continue the work.

6.3 Training and Education
The PM team enables technician training on both the team’s shift and the concurrent shifts. A new technician must learn both preventative maintenance activities and trouble shooting. Intel sends many equipment technicians to outside training courses but, without the routine practice and guidance from senior technicians, it is unrealistic to expect a new technician to be confident in all PM activities. The PM team is an excellent training ground for new technicians because it provides technicians with the opportunity to repeatedly practice PM activities and be mentored by skilled technicians. New technicians on the standard shifts also have the opportunity to gain experience performing PM activities during their shift.
6.4 PM execution methodology

The PM team’s primary goal is to drive continuous improvement and standardization through PM activities. Just the creation of the team created a significant improvement in PM activity durations because PM’s could be preformed 24 hours as a result of the new skilled technician configuration. The team continuously worked through the 8 key HPM initiative attributes described in the previous chapter.

Tool Kits

The ownership and responsibility of tool boxes is one of the largest challenges the PM team faced. There are a number of large tool boxes which all shifts share. Each drawer is labeled with the type of tool which belongs in the drawer i.e., US and metric wrenches. Without further organization, it is difficult to locate specific tools within each drawer.

One step the PM team took was to create tool kits for each type of tool. The kits were stored in small portable tool boxes and contained 12 to 15 key tools frequently used in PM activities. The tool boxes had a picture attached to the lid of all the tools assigned to the tool kit. The team still had difficulty taking ownership of the tool organization. Foam cutouts for the tool boxes which keep tools in order could benefit the kitting effort.

Parts Clean

Area C has a large number of assemblies which are replaced with clean assemblies during PM activities. The area which cleans these assemblies, Parts Clean, is located in the sub fab. The distant proximity of Parts Clean from the Area C forces the two departments to communicate using beepers, email and telephones. The naming convention for the assemblies, which is different between Area C and Parts Clean, has in the past generated confusion.

The PM team and the Parts Clean department worked to alleviate some of these issues by creating assembly tags which could be used to communicate which Parts Clean
technician cleaned the assembly and if there was an issue with the assembly during a PM, what the issue was and which equipment technician had made the comment. Assigning responsibility for these assemblies to specific technicians helped to open channels of communication.

The improved communication between the two departments also increase interdepartmental meeting to discuss the standardization of Parts Clean processes. Parts Clean was in the process of training new technicians and the feedback from Area C equipment technicians helped to improve Parts Clean training classes. The root of the problem for Parts Clean is that the department does not have clear specifications for training technicians on the proper method for cleaning assemblies. Creation of these specifications is going to be a very large project but will be extremely beneficial in reducing defects.

Run the PM

Run the PM, often abbreviated RTPM, is a HPM process performed by equipment technicians and equipment engineers to standardize PM activities. Commonly, changes are made to PM specifications but the sequence of steps in the document are not re-evaluated. Just recently, Area C reduced the time it took to take a tool down by eliminating 50% of the cooldown time. Typically during the cool down, equipment technicians would collect their tools and replacement parts. Now with the shorter cool down period, there was not enough time to collect all the tools and parts needed. Some equipment technicians adjusted and prepared in advance while others still followed the same process allowing the tool to cool down for longer than necessary. During a RTPM event, advanced technicians perform a single PM while the remainder of the technicians and equipment engineers watch. As the technicians step through the specification sequence document, they evaluate as a group the most efficient way to perform a PM. At the end of the session, the group agrees on a standardized method to perform the PM and the specification document is edited to reflect decisions made during the meeting. The
RTPM event standardizes the process by which all area equipment technicians perform the PMs and helps to minimize the variability in time when tools are in PM activities.

6.5 Data Systems

The team maintains spreadsheets which track the preventative maintenance down time for each type of PM, the availability and A80 for each tool group. The availability and A80 metrics are a holistic performance indicator for the tool group because they reflect total tool up time. Total tool up time is affected not only by PM activities but also unscheduled maintenance and engineering activities. Engineering activities during the 6 month PM team ramp up included elimination of significant amounts of post PM tool qualifications and reduction in PM activity frequency. Below is the availability and A80 chart for the two tools in Area C which were identified by the D2 HPM initiative as having significant effects on wafer cycle times and potentially benefiting from the HPM program. While the two indicators are not great metrics to evaluate the performance of the PM team, they do show the success of the HPM initiative in the tool groups.

Tool D A80 metrics indicate that the A80 increased by an impressive 9.3% during the 6 month HPM initiative introduction. Tool E increased by a slightly less impressive 5.7%. Interestingly, while Tool D was able to maintain a relatively constant A80 improvement, Tool E’s A80 metrics is slipping throughout the entire 6 months.

The availability of Tool D and Tool E reflects their A80 metric. Tool D shows a clear increase of 6.5% in availability which is also characterized by reduced variability. Tool E shows no increase in the availability during the 6 months after the start of the PM team.
Figure 8 PM Progress Tracking

D2 Area C Availability Chart

Tool D increase 6.5%
Tool E increase 0%

D2 Area C A80 Chart

Tool D increase 9.3%
Tool E increase 5.7%

Pre WW25
Tool D Avail Avg 49.5%
Tool E Avail Avg 50.0%
PM Team Start WW25
Tool D Avail Avg 58.8%
Tool E Avail Avg 56.3%

Pre WW25
Tool D Avail Avg 62.8%
Tool E Avail Avg 71.3%
PM Team Start WW25
Tool D Avail Avg 71.9%
Tool E Avail Avg 70.8%
In addition to tracking each tool group’s A80 and availability, the team also tracks how individual PM’s compared to the target down time, other previous PM’s and the break out of logged down time. Above is a chart which shows the Tool D PM F chart. The grey bars represent PM Fs which were either preformed prior to the PM team or not by PM team members. The bars broken out into different colors show PM Fs preformed by the PM team.

One of the key issues which faces the Area C PM team is the low frequency and high variation of PM activities within the area. The most frequent PM activity occurred every 2 months and there were over 10 different PMs for Tool D and Tool E. It was difficult for the team to gauge its success on a PM activity when the last PM of that type occurred over 6 months ago.
6.6 Conclusion

The PM team is effectively organized to assign ownership of the PM activities to equipment technicians on the team. The team’s mid week schedule overlaps with the other shifts to provide both support and improved communication between the shifts. The team undertook a number of initiatives to improve the day to day operations of Area C. These initiatives included training of other technicians, creation of tool kits, and improved relationship with the Parts Clean group. The metrics used to track the team’s success were created and managed by the team. The incentive the team took to improve the area’s operations show the team felt a sense of ownership for the PM activities.
Chapter 7: Observations and Recommendations

The HPM initiative is an extremely well designed program that has the ability to reduce wafer throughput times across the entire factory. The success of the initiative is highly dependant on the participation of equipment technicians to improve and standardize preventative maintenance activities. The PM team creates an environment where some of the factory’s most skilled technicians can collaborate to drive standardization through preventative maintenance activities. Expanding the program throughout the entire D2 factory would help drive the HPM initiative deeper into the factory’s culture.

7.1 PM Team Expansion

The PM Team is an excellent use of resources and if proliferated throughout D2 could improve wafer throughput. Not only does the PM Team focus on implementation of the HPM initiative but it also recognizes highly skilled equipment technicians. The PM team program will have the greatest affect if it is first expanded to areas with high availability variability identified by TAC-TOOT and then throughout the remainder of the factory. The success of the PM team expansion will depend on three critical components: team ownership, management support and proper implementation of continuous improvement metrics.

Team Ownership

The PM team will be most effective if it is given complete ownership of the scheduling and preventative maintenance activities. This means that the team will still work closely with equipment engineers and shift managers but the preventative maintenance final scheduling decisions will be made by the PM team. Giving the PM team the power to operate the area’s preventative maintenance will assign the success of the preventative maintenance activities to the PM team members.
A rotation of the area’s advanced equipment technicians through the PM team will allow all technicians to have a chance to participate. Initially, when the team is first starting, capable equipment technicians will be asked to participate on the team but, ultimately a position on the PM team should be sought after and technicians will volunteer to participate on the team. Having the PM team’s weekly shift scheduled during desirable shifts will help motivate technicians to participate on the team.

As was discusses earlier, many of the skilled equipment technicians at D2 have reached the top of their pay scale. It has been a challenge for management to continue to satisfy the career aspirations of these technicians. Offering them the opportunity to participate on the PM team with complete ownership of the preventive maintenance activities will be an excellent opportunity for Intel to recognize them as highly valued equipment technicians.

Management Support

The support of the factory management is the second key component to the PM Team’s success. The collaboration of equipment engineers with the equipment technicians will enable the PM team to align the preventative maintenance activities with the HPM initiative. The collaboration of the two groups will bring together the practical knowledge of the equipment technicians with the theoretical knowledge of the equipment engineers. Together, the two groups will be able to make significant improvements to preventative maintenance activities’ sequencing and repeatability.

While the key support relationship will be between the equipment engineers and the PM team, it is important for the equipment technician’s direct supervisor to be involved in the support of the PM team. The supervisors can act to drive continuous improvement as well as interact with other PM team managers to learn about their team’s successes. Currently, many of the shift supervisors meet at a weekly HPM meeting where they share their area’s progress. In the future, it could be beneficial to have higher equipment
technician participation at these meetings because it will allow them to learn directly from each other and less through third parties.

In order to give the PM team ownership of the scheduling and planning of the preventative maintenance activities, some responsibility could be removed from the FAMs, shift managers and equipment engineers. These groups may resist releasing the ability to schedule preventative maintenance. One explanation for the change in responsibilities could be that their core responsibilities are not tied to individual preventative maintenance activities but to broader scale functionality of the entire area. The time that they would have previously spent negotiating scheduling can now be used for supporting the PM team.

**Continuous improvement**

The implementation of performance metrics will help the PM team drive continuous improvement. The current metrics, tool average availability and A80 can be modified to reflect the PM team’s individual performance. PM Team metrics could include

- Preventative Maintenance tool down time variability by PM type
- Percentage of Waddington effect (An unscheduled tool downtime attributed to a poor preventative maintenance)
- Run the PMs performed each month

There are already some web tools which track these metrics for each area. Unfortunately many of the company wide web tools can not be customized for individual areas. Whether the teams use a web tool or spreadsheet, it is important to gaining consensus on these metrics from each area.

**7.3 Future Areas of Research**

The metrics used to gauge the success of each PM team need additional development and validation. Part of what makes the PM team metrics difficult is that each area has
different challenges. Capturing all of these challenges in one set of metrics which is valuable to every area will be important.

7.4 Conclusion

The PM team program adds tremendous value to the HPM effort. It utilizes the knowledge of experienced equipment technicians to help standardize preventative maintenance activities. The expansion of the program to the entire factory could help all areas to strengthen their HPM effort. Three key components to the team’s success are team ownership, management support and continuous improvement. Allowing the PM team to own the preventive maintenance activities will help assign responsibility of the success of each activity to the team. The management support of the PM team will empower the team to improve standardization of preventative maintenance activities. One area of future research, critical to the team’s success, is the development of performance metrics to drive continuous improvement.
References

Allen, David E. and Capellen, Rachelle, “Improving output capability through minimizing variability in an HVM fab”, IMEC, 2005


Appendix A: Cycle time distribution of 28 Average Daily Periods for 35 randomly selected processes
Appendix B: Cycle time distribution of 14 Average Daily Periods for 35 randomly selected processes
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Appendix C: Availability distribution of 28 Average Daily Periods for 11 randomly selected processes
Appendix D: Availability distribution of 14 Average Daily Periods for 11 randomly selected processes