Lean Manufacturing in a Semiconductor Environment:
Use of Variation Analysis to Focus Continuous Improvement Efforts
by
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Submitted to the Department of Mechanical Engineering
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In Partial Fulfillment of the Requirements for the Degrees of

Master of Science in Ocean Engineering
Master of Business Administration

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Abstract
Intel’s FAB 17 (F17), in an effort to remain competitive and reduce production cycle time, recently committed to adopt lean manufacturing as their approach to continuous improvement. To aid in this effort, the factory staff has dedicated a group people to develop tools based on lean manufacturing principles. Over the last 18 months, they have created three systematic approaches to address various forms of throughput variation, Autonomous Manufacturing (AM), Planned Maintenance (PM), and Waste Elimination (WE). Autonomous Manufacturing focuses on refurbishing manufacturing tools to new or better condition, up-skilling manufacturing technicians, and differentiating abnormal from normal operating conditions. It is meant to address throughput variation as a direct result of old, poorly maintained tools. Planned Maintenance focuses on keeping refurbished tools in new or better conditions, level loading maintenance activities, and minimizing manufacturing tool downtime due to scheduled maintenance activities. It is meant to address throughput variation as a direct result of tool availability variation. Finally, Waste Elimination focuses on optimizing the flow of information, people, and material. It is meant to address throughput variation as a direct result of inefficient flow through the manufacturing process.

This thesis provides an overview of F17’s lean journey. It shows that F17 has done an excellent job of developing an infrastructure to support their lean transformation. Going forward, their major challenge will be ingraining the new principles into the existing organizational structure. A variation analysis approach uses a simple model of daily production of an operation, several key metrics that relate work in progress (WIP) flow to tool performance, and a graphical display of WIP flow and tool performance. A case study conducted identifies the most probable source of throughput variation as arrivals at one operation, tool performance at another operation, and WIP management at a third operation.

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Chapter 1: Introduction

This chapter provides background on Intel Corporation, the motivation for the internship, an overview of the issues the internship is intended to address, and an outline for the remainder of the thesis.

1.1 Intel Corporation

Founded in 1968, Intel Corporation (INTegrated ELectronics), sought to design, develop, and manufacture cutting edge semiconductor based electronic components. While initially focusing on memory products, Intel has built up significant brand recognition and customer loyalty by continuously providing the market with leading edge microprocessors, such as the Pentium and Centrino product lines. The first to market with new technology strategy has provided Intel with significant competitive advantage and has driven up customer’s willingness to pay for these products. Each new technology generation reduces feature dimensions by 0.7 times, increases transistor density by 2.0 times, and increases switching speed by 1.5 times, all of which increases processor performance, reduces power consumption, and reduces manufacturing cost by reducing area per die. Figure 1 (F17 Comm. Dept., 2003) shows the typical technology ramp pattern for microprocessors and chipsets. (Chipsets are integrated circuits that perform one or more related functions to support a computer’s microprocessor.)

![Figure 1: Technology Ramp Cycle](image)

The first peak in the cycle represents microprocessor volumes. The second peak in the cycle occurs as chipset volumes transfer from one technology to the next. Note: This graphic is for illustration purposes only; peak sizes are not to scale.
New process technology is closely related to new equipment. Every 10 to 12 years a new wafer size, i.e. 200mm, is introduced. The introduction of a new wafer size also accompanies the ramp of a new process technology. In 2003, Intel launched 90nm process technology and made the decision to only run this technology on 300mm wafer processing equipment. The combination of new process and equipment technology positions Intel to provide the market with leading edge technology.

As mentioned above, Intel competes externally through its first to market strategy by launching new process technology approximately every two years. Internally, the 11 fabrication facilities (fabs) worldwide compete to receive production volume, new products, new process technology and new processing equipment. They compete on metrics such as cost, quality, yield, and productivity to name a few. Those fabs that excel in all areas are rewarded with increased production volume or wafer starts per week. If they continue to be successful they are granted new products, new process technology and eventually new processing equipment. The latest source for major inter-fab competition has been for 300mm wafer process technology. Converting a 200mm fab to a 300mm fab requires an investment in excess of a billion dollars and guarantees the long term viability of the manufacturing site. If a 200mm fab is not placed on the roadmap for 300mm, it is at a distinct productivity disadvantage and will be at risk for shutdown (Fearing, 2006).

1.2 Internship Motivation

During the summer of 2003, F17 sought about developing a new manufacturing strategy that would allow them to be successful without the productivity and technology advances provided by new tooling or significant capital expenditures. The factory staff settled on implementing the methods of continuous improvement developed by Toyota, popularly known as lean manufacturing, and branded manufacturing eXcellence (mX) by Intel. To assess and provide feedback to their progress, F17 sponsored an internship with the Leaders for Manufacturing Program at Massachusetts Institute of Technology. In doing so, they hoped to achieve the following goals:
• To understand the successes and the future opportunities for improving the current implementation effort;
• And, to establish a structured approach to improving operational flow in an area;

1.3 Problem Statement

F17's wishes to transform the way their employees engage in continuous improvement activities. To aid this effort, this internship seeks to address the following problems.
• Every employee needs to be involved in continuous improvement activities
• mX will be the method used by managers and technicians to achieve successful continuous improvement throughout the site
• The change from current management practices to those advocated by mX will be a long term organizational change and will occur in stages
• Implementation sustainability is of utmost concern
• Variability in WIP arrivals, tool performance, and personnel capacity to utilize tools contribute to throughput variation. Current area performance metrics do not reliably identify the source of throughput variation

1.4 Thesis Overview

The following will describe the content of the remainder of this thesis.

Chapter 2 provides a history of F17, a look at the markets F17 competes in, and builds the business case for pursuing lean manufacturing.

Chapter 3 explains the existing organizational structure and outlines how the mX structure has been developed.

Chapter 4 describes the tools developed by the mX group for use in improving tool performance or operational flow in an area.

Chapter 5 outlines the variation analysis tool developed to assist in prioritizing organizational effort. Three examples display the application of the tool in identifying the most applicable improvement activity for a given area.
Chapter 6 reviews the findings and provides additional recommendations for F17 in focusing organizational effort and leading the organizational change.
Chapter 2: A Brief History of FAB 17

This chapter will review F17’s history as a high volume manufacturing site, the competitive markets in which F17 competes, and the business case for engaging in a lean manufacturing strategy.

2.1 Intel and F17

F17, located in Hudson, Massachusetts, started as Digital Equipment Corporation’s (DEC) Hudson Manufacturing Facility. The site, originally developed in 1977, was built into the modern semiconductor manufacturing facility it is today in 1995. From 1995 through to 1997, the Hudson site manufactured microprocessors for use in the computers built by DEC. In 1997, Intel announced the purchase of DEC’s semiconductor operations and integrated the Hudson site as F17 (F17 Comm. Dept., 2003).

From 1998 until 2003, F17 stayed on the cutting edge of Intel technology eventually receiving 130nm process technology. Since then, production volume has slowly transferred from the high revenue microprocessors to the commoditized chipsets that support them. By 2005, 20% of F17’s production volume consisted of microprocessors with the remaining 80% made up of chipsets. During the summer of 2005, Intel announced a $250M investment in F17 to support a 50% increase in chipset production volume. By the end of 2006, nearly 95% of F17’s production volume will be made up of chipsets.

2.2 Chipset Market Overview

Intel’s primary product is microprocessors in which they enjoy a market share in excess of 80% (Shankland, 2005). Microprocessors, the central brain of a computer, are typically the most costly component. Chipsets, on the other hand, are the semiconductor based chips that act as a computer’s “nervous system” (Intel Annual Report, 2004) and provide processor interface with the outside world. They effectively translate the signals supplied by I/O devices to the processor to provide the core-logic interface functions between the microprocessor and the rest of the system.
The first chipsets were developed to offload memory functions carried internally on microprocessors. The offloading of these memory functions allowed for increased processor speed. Chipsets were used because they could be positioned closer to the processor and responded several orders of magnitude faster than hard drives, the only other option for memory storage. Chipset functionality slowly expanded beyond simple off processor memory storage to include graphics, user interface devices like keyboards, and other high speed interface functions. Today, chipsets manufacturers seek to exploit advances in processor technology and thereby improve customer experience at the user interface by enhancing chipset functionality (Kissel, 2005).

Process technology for chipsets generally lags that of processors by several years. This results in lower barriers to entry, because older and therefore fully depreciated, process equipment can be used for manufacturing. For example, leading edge microprocessors are currently manufactured by Intel in high volume using 90nm technology. Chipsets are still manufactured at several sites using 350nm technology, a process that is 4 generations behind that of processors (Intel Annual Report, 2004). To protect their market position in chipsets, Intel aggressively protects their processor/chipset interface designs through the patent process. This action forces competitors, seeking to supply chipsets to support Intel processors, to license the interface designs from Intel. The results are significant advantage in time to market and performance of Intel chipsets versus their competitors and 64.5% share of the market. In spite of Intel’s aggressive strategies, competition remains fierce as demonstrated by the 4.2% decline in average chipset price to $21.87 by the end of 2004 (Rau, 2005).

2.3 For What Purpose? - The Business Case for Lean

In making the decision to pursue a lean manufacturing strategy, businesses develop a case that provides an overarching motivation for the strategic shift. Typically the business case culminates around competition and customer responsiveness and their effects on cost structure. Intel as a corporation does not have broad support to implement lean on a corporate level. This is due to the business case. For most of Intel’s manufacturing facilities, especially those on the 300mm road map, they manufacture differentiated
products, specifically microprocessors. Consumers purchase computers based on microprocessor performance and are willing to pay a premium for leading edge products. Intel's first to market strategy perfectly aligns with the needs of the market and allows them to set the price for their products using the price equation:

\[
\text{Price} = \text{Cost} + \text{Profit Margin.}
\]

Here, profit margin is controlled to maintain profits. While manufacturing costs for high revenue products matter, they are insignificant to other metrics such as yield and productivity or more importantly, process technology time to market.

Chipsets, contrary to microprocessors, are less of a differentiated product. They have slower product development cycles and less differentiation among competitors. Customers do not purchase computers based on the type of chipsets. This results in customers with a much lower willingness to pay and shifts the economics of the market. In this new market the profit equation is:

\[
\text{Profit Margin} = \text{Price (fixed or falling)} - \text{Cost}
\]

As mentioned above in section 2.4, prices in the chipset market fell between 2003 and 2004 by 4.2%. Thus the key to profitability is Cost Reduction (Dennis, 2002). And the only source of competitive advantage is the rate of continuous improvement of cost structure. For Intel this translates into reducing cycle time as a main cost driver. To illustrate this point, consider Intel's 2003 and 2004 raw materials, work in progress, and finished goods inventory levels, shown below in Figure 2. Clearly, the large majority of Intel's inventory investments are contained in WIP, with nearly 85% of total inventory held in WIP and finished goods. This leaves Intel with a large quantity of product with high holding costs and at high risk for obsolescence (Intel considers all product with excess demand within a rolling six month horizon to be valueless)(Intel Annual Report, 2004).
The decision not to convert from 200mm to 300mm has not affected the short term viability of F17. Since the decision, production volume has been shifted from microprocessors to chipsets. As mentioned earlier, Intel recently rewarded F17’s performance since 2003 by investing $250M in additional 200mm process equipment and increasing their production volume by 50%. While these short term successes are encouraging, the increased investment and production volume do nothing to establish F17 as a high volume manufacturing site with long term viability. To address this short fall, the factory staff decided to take proactive action and pursue a lean manufacturing strategy in 2004. This decision was made for one main reason: Building an organizational capacity to continuously improve will become F17’s source of competitive advantage. Since then, members of the factory staff along with a dedicated mX implementation team set about developing the tactics to achieve the new mX strategy.
Chapter 3: mX at F17

This chapter reviews F17’s Plant and Manufacturing organizational structure. It will also discuss the method used to develop an organizational infrastructure to support the mX initiative.

3.1 F17 Organization

F17 processes 200mm wafers in lot boxes of 25 wafers, 24 hours a day, 7 days a week. The Plant Manager carries overall responsibility for day to day operations of the fab. Reporting directly to the Plant Manager is the factory staff. The factory staff consists of Department Managers for Manufacturing (Mfg), Special Projects, Process Engineering (PE), Yield and Sort, and Manufacturing Systems Engineering (MSE) as well as various other support functions such as Finance and Human Relations. Group Leaders, or Shift Managers in the case of Manufacturing, report to each Department Manager. The Group Leaders are responsible for managing salary direct reports. In manufacturing, Shift Managers manage Operations Managers. Operations Managers are the front line managers that coordinate the tactical production and maintenance operations on a day to day basis. In process engineering, Group Leaders manage functional area Process Engineers. Process Engineers are responsible for internal “recipes” that the technician and/or tools use to process wafers through an operation. Figure 3 below provides a basic outline of the organizational structure. Note: This chart is intended as an example and is incomplete.

Figure 3: F17 Organizational Chart
In addition to this structure of direct reports, there are other organizational structures used to provide cross functional support where needed. One example is the Functional Area Coordination Meeting (FACM) structure. This meeting consists of Manufacturing Manager, Shift Manager, assigned process engineers and engineering group leaders. Reporting to the FACM is the Group Leader Operations Manager (GLOM) forum. GLOM's consist of Group Leaders across several functional areas, the responsible Operations Managers that tactically manage those functional areas, and an assigned Shift Manager with expertise in the area. Reporting to the GLOM is the Module Team (MOD Team). The MOD Team consists of aligned Process Engineers, an Operations Manager, and Manufacturing Technician representatives from all 4 manufacturing shifts. Members of these teams typically work on issues that effect WIP flow, manufacturing tool performance, and overall area operations. Figure 4 below outlines the FACM – GLOM – MOD Team Structure.

![FACM Organizational Structure](image)

The FACM structure is an excellent example of how Intel seeks to provide an infrastructure to support factory wide initiatives with cross functional support.

### 3.2 mX Infrastructure Development

In early 2004, following the decision by Intel to keep F17 off the 300mm roadmap, the factory staff began to discuss the future of F17. Several engineers in the organization, with experience in Total Productive Maintenance, recommended experimenting with techniques of lean manufacturing. Those engineers planned and executed a learning lab with 10 people that ranged from front line technicians to members of the factory staff.
The Learning Lab convinced members of the factory staff that lean manufacturing/mX was the path F17 should take to insure long term viability.

Following the Learning Lab, an mX steering committee and dedicated mX Implementation Team was formed. The newly formed Implementation Team, through low cost experimentation entitled the Management Model, began development of a structured approach to improving area performance. They started with work place organization efforts in three functional areas of the factory. The effort had several goals. First, the Implementation Team wanted to understand the dynamics of operating a team consisting of shift managers, operations managers, and members of factory staff all physically working along side manufacturing technicians as peers. Second, they wanted to develop a robust, structured approach that area managers could easily use in other areas of the factory.

Following the Management Model, the Implementation Team moved into Wave 2. Wave 2 expanded the learning captured in the Management Model and launched the first pilot manufacturing equipment improvement and maintenance level loading experiments. Wave 2 also had several goals. First, the Implementation Team wanted to expand front line management understanding of the mX initiative while adapting key learning from the management model. Second, they wanted to develop a robust, structured approach to improving tools to new or better condition, upskilling the workforce in the operation of the tools, and developing inspection criteria that clearly defines normal from abnormal operating conditions. Finally, they wanted to develop an understanding of how quick change over and planned maintenance level loading activities could decrease tool downtime for planned and unplanned maintenance.

### 3.3 mX Organizational Structure

One outcome from the significant work done by the Implementation Team was the development of the mX Organization. In terms of direct reports, the mX group reports to the Special Projects Department Manager, see Figure 3, and consists of a group leader and 4 to 6 Implementation Team Members. Functionally, the mX group provides an
interface between the mX Steering Committee and the manufacturing organization. Each member of the Implementation Team is responsible for leading implementation efforts for at least two functional areas in the factory. Their role to date has been to deliver training on mX philosophies and drive implementation activities across all 4 manufacturing shifts. Figure 5 below shows the functional mX organizational structure.

![mX Organizational Structure Diagram](image)

Figure 5: mX Organizational Structure

Using a separate organization has allowed F17 to develop and role model how managers and frontline technicians should engage in continuous improvement activities. The next challenge is transferring the learning captured through the mX implementation experience to the broader organization.

### 3.4 Implementation Model

The model that F17 has adopted to implement Lean Manufacturing is based on Toyota's initial work with Total Productive Maintenance (TPM). As with Toyota, F17 postulated that equipment variation was the main source of manufacturing process stability. To address this concern and explore how a "lean" semiconductor Fab would look, the factory staff coupled with several key contributors educated in TPM began to apply the implementation framework they are using today.

The framework used at F17 focuses around two core points. First, the best lessons are self-concluded through learning by doing. And second, engage the problem at the point
of activity with the people who are the experts in the process, the frontline workers. To capture the learning as each new activity occurs, they structured and reflect on their activities as they are completed. They then seek to replicate the successful actions and improve the areas that fell short of the mark. Figure 6 below shows the author’s representation of this cycle graphically.

![Implementation Framework Diagram]

**Figure 6: Implementation Framework.**

The core of the framework lies in the engagement of an mX team member at the point of activity with key stakeholders in the area. Their role in the implementation is three fold. First, through low cost experimentation, develop the training content to grow organizational knowledge of the lean effort, its philosophies, and its tools. Second, lead the implementation effort at the ground level providing the initial momentum to get the implementation going. And finally, professionally develop the key stakeholders in the areas such that the implementation becomes self-sustaining.

From this effort, F17 hopes to develop a unique organizational capability to organically learn from and improve its operational environment. When successful, this capability will be exceptionally difficult to duplicate, thus providing F17 with a resource for longer term viability.
Chapter 4: Lean “Tools”

Since early 2003, F17's mX group has experimented with and developed several systematic approaches, referred to commonly as Lean Tools, for improving specific problems within an area. These approaches are Autonomous Manufacturing, Planned Maintenance, and Waste Elimination. This chapter discusses why these Tools have been developed and what problem they are intended to solve.

4.1 Autonomous Manufacturing

Early in the development of mX at F17, the question was asked, what is the cause of our long process cycle time. The answer: the variation in tool performance. This conclusion was drawn based on some loose analysis and the direct experience on the shop floor. To quantify this judgment, management points to the fact that, in the current state, more than 50% of maintenance activities at F17 is breakdown, or unscheduled, maintenance. Unscheduled maintenance is a problem for two reasons. First, it reduces average daily capacity. Second, tools may breakdown during the processing of WIP and can cause defects which lead to rework and scrap. In the ideal state, breakdown maintenance would make up 0% of the maintenance time expended. Autonomous Manufacturing (AM) was developed to structure the activity of eliminating unscheduled down time. The structured activity provides a process for identifying factors that contribute to tool failures as well as a mechanism for eliminating them (Koch, 2003).

The contributing factors that lead to tool failures are identified through a series of increasingly intrusive inspections. The inspections start with the exterior portion of the tool and get progressively deeper with each pass. The scope of each pass is defined by a cross functional team consisting of those responsible for the area’s performance to include operations managers, process engineers, manufacturing technicians, and potentially shift managers and group leaders from across each shift. To provide a mechanism for resolving the defects, a series of facilitated and independent technician/manager/engineer meetings were developed. Following the inspection of the tool, these shift teams developed temporary solutions to the problem. After the defects are corrected, the teams decide whether a root cause analysis is required to understand the
source of the defect. Once root cause is discovered by the team, countermeasures are proposed to resolve the issue. The proposed countermeasures are presented to members of the original four shift team and an implementation plan is developed. Several weeks after implementation, members of the team follow up on the countermeasure to check if it resolved the issue. If the countermeasure failed to resolve the defect, the process is repeated until an effective countermeasure is developed. Successful countermeasures are then standardized across all shifts.

Through this process, the technician and engineers responsible for the operating condition of the tool, improve the tool's performance. By structuring the activity of refurbishing the tool to new or better condition, the team is expected to identify critical inspection points and operation standards that may not be in place or are not clearly understood. By involving all technicians across all four shifts, process engineers, and operations managers in the process, high agreement on the difference between normal and abnormal operating conditions can be developed. Increased skill levels will also be recognized as the team understands how to maintain the material condition of each tool.

The intent of AM is to increase the average capacity of a tool by eliminating unscheduled downtime events. Figure 7 shows a possible capacity profile of a generic manufacturing tool. As shown, daily tool capacity will have an average and standard distribution of capacity.

![Figure 7: Tool Capacity Probability Distribution](image)

This figure shows the intended impact of AM activities on a tool.
In addition to increasing average capacity a secondary effect of increased mean time to failure should also be observed. Assuming that the arrival rate to an operation does not significantly change, the combination of increasing capacity and mean time to failure will reduce throughput variation (Gershwin, 1994).

4.2 Planned Maintenance

Planned Maintenance has been developed to drive tool maintenance to the ideal state where restored tools stay in new or better condition, capacity does not vary due to maintenance activities, and total scheduled downtime is minimized. To achieve this ideal state, teams, similar to those used in AM, use activities such as level loading, quick change over procedures for maintenance actions, and coordination of maintenance activities across manufacturing tools to minimize the impact on system throughput. Additionally, failure mode analysis may be used to identify and eliminate failure modes not addressed during the first AM activities (Koch, 2003).

The intent of PM activity is to narrow the daily distribution of capacity by decreasing unplanned down time and the variation in planned maintenance. Level loading planned maintenance, the act of breaking down large infrequent maintenance activities into smaller more frequent chunks, will be used to illustrate how this occurs. Assume that a given annual maintenance action requires 26 hours. This may be easiest for the technician as it clumps maintenance activity into a single block of time; however it increases capacity variation due to long repair down states which in turn increases line variability (Gershwin, 1994). Less line variation will occur if the maintenance action can be broken down to 30 minutes every week. Figure 8 shows how PM activity in an area intends to affect an area’s performance.
The first curve is an assumed probability distribution of WIP arrivals at a given operation. The second curve is a probability distribution of tool capacity. If the two distributions overlap, then there is a non-zero probability that on any given day WIP arrivals will exceed the available capacity to process that WIP. This non-zero probability will tend to increase throughput variability and increase total product cycle time. By decreasing the variation in planned maintenance, the daily distribution of capacity is narrowed and the probability of arriving WIP experiencing a blocked state is decreased.

4.3 Waste Elimination

Contrary to PM and AM, Waste Elimination (WE) looks to improve the flow of information, material, and people (Koch, 2003). This is done through a repetitive process: Waste Identification; Definition of Current and Ideal State; Set Goal, Scope, and Boundary Conditions; Problem Analysis and Countermeasure Development; Implementation and Confirmation; Recurrence Prevention; Horizontal Replication. Based on Plan-Do-Check-Act (Shiba & Walden, 2001), this process will engage the workforce in continuous improvement at the point of activity with the process experts.

The intent of WE is to increase the workforce’s capacity to do work, smooth WIP flow through an area, and optimize WIP flow from area to area. Figure 9 shows a graphical representation of the type of affect that WE can have on a work area.
Figure 9: Arrival, Capacity, and Technician Capability Probability Distributions

Here the first curve is the probability distribution for WIP arrivals at an operation. The second curve is the probability distribution of technician capability to process these WIP Arrivals. The third curve is the probability distribution of equipment capacity to process the WIP arrivals. Using this model, the available capacity of an area will correspond to the smaller of people capability and equipment capacity. (Note: Measurement of people capability to conduct work in an area cannot be accomplished using remote metrics. Understanding the people component of work requires direct observation of the work environment.) As shown, WE intends to increase the average and narrow the standard deviation of technicians capacity to work by systematically identifying and eliminating waste in daily processes. WE can also be used to increase the capacity of equipment by eliminating or minimizing activities that result in lost capacity at a given tool.

4.4 Conclusions

The previous sections describe various approaches to improving the performance of an area. Autonomous Manufacturing improves tool operation by refurbishing tools to new or better conditions while increasing operator skill level in recognizing normal from abnormal operating conditions. This approach effectively eliminates unscheduled downtime and increases the mean time to failure. Planned Maintenance improves the performance of the maintenance system and keeps refurbished tools in the restored condition. By understanding new failure mechanisms, level loading maintenance
activities, and working on quick changeover procedures, the variation of tool capacity is
minimized. Waste Elimination focuses on the flow of information, material, and people
in an area. By using structured on shift problem solving, inefficiencies can be identified
and eliminated, thus increasing the capability of the entire area. The only unanswered
question is, what should an area work on first?
Chapter 5: Variation Analysis

This chapter discusses current area performance measures used at F17 and proposes an analysis approach to identify throughput variation that will allow area managers and technicians to focus improvement efforts on the source of throughput variation.

5.1 Existing Metrics and Prioritization Methods

Intel and F17 use a variety of ways to understand equipment and area performance. This information is then used to prioritize the type of improvement work an area should undertake. Figure 10 below describes the indicators, their units of measure, benefits, and drawbacks.

<table>
<thead>
<tr>
<th>Description</th>
<th>Benefits</th>
<th>Drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Areq</strong></td>
<td>Availability Required - Minimum availability required to meet factory loadings and line pace goals on a weekly basis</td>
<td>Easily communicated requirement, Easy to understand</td>
</tr>
<tr>
<td><strong>A80-Areq</strong></td>
<td>Difference between the 80th percentile of availability and minimum average required availability over specified timeframe</td>
<td>Easily communicated measure of performance, takes tool variability into account</td>
</tr>
<tr>
<td><strong>OSWreq</strong></td>
<td>Outs/System/Week - Wafer outs target by each tool per week (168 hrs), set by F17</td>
<td>Easily collected, easy to communicate measure of performance</td>
</tr>
<tr>
<td><strong>Cycle Time</strong></td>
<td>Time required to process raw material into finished goods, typically expressed in terms of WIP Tums</td>
<td>Easy to communicate requirement, Easy to understand</td>
</tr>
</tbody>
</table>

Figure 10: F17 Required Equipment Performance Indicators
(Note: The term “Not Normalized” above means that the metric from one tool area cannot be directly compared to another)

Required equipment performance indicators are compared to Model of Record (MOR) metrics. The Model of Record provides availability, utilization, A80 and OSW requirements based on theoretical calculations of throughput at a specified load level.

For example, the Model of Record for tool type Z may require 5 tools with an average availability of 80% and utilization of 75% to meet the capacity requirements of a 5000 Wafer Starts Per Week (WSPW). In this case, each tool, with an average availability of 80% and utilization of 75% has a capacity of 1000 wafers per week. The Model of
Record can also be adjusted to better match actual capacity conditions. For example, at a factory load level of 5000 WSPW, tool Z actually has 7 tools in the factory. To meet the capacity requirement, the MOR can be reduced to an average availability of 60% and utilization of 55% to better match the actual requirement. Figure 11 explains Model of Record metrics.

<table>
<thead>
<tr>
<th>Description</th>
<th>Benefits</th>
<th>Drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Availability</td>
<td>Virtual Factory (VF) collaboration that sets tool availability target on the basis of demonstrated capability</td>
<td>Not normalized, single static number based on theoretical calculations, provides binary information, did the area's tools perform to the model specifications (Y/N)</td>
</tr>
<tr>
<td>Utilization</td>
<td>VF collaboration that sets tool utilization target on the basis of minimum requirements to meet WIP Turn goals?</td>
<td>Not normalized, based on theoretical calculation, accuracy is questionable with increased product mix, actual utilization may vary based on availability of WIP</td>
</tr>
<tr>
<td>A80</td>
<td>80\textsuperscript{th} percentile of availability spanning a 7 day timeframe or 28 day timeframe</td>
<td>Not normalized, need to understand probability to understand metric, based on past performance, does not predict future performance</td>
</tr>
<tr>
<td>OSW</td>
<td>Wafer outs target by each tool per week (168 hrs), set by VF collaboration</td>
<td>Not normalized, provides binary information did an area make their outs (Y/N), based on past performance, does not predict future performance</td>
</tr>
</tbody>
</table>

Figure 11: Model of Record Equipment Performance Indicators

Performance improvement requirements are prioritized in several ways: predicted capacity shortfalls base on the Model of Record, actual equipment performance compared to the Model of Record and tools with an unacceptably low A80 as identified by A80-Areq. All of these methods of prioritizing improvement efforts focus on equipment performance. This implicitly assumes that the static models correctly reflect the dynamic reality of the production floor.

To prioritize the mX implementation effort, the mX Steering Committee used A80-Areq to identify tools in need of performance improvement. The assumption was that tools with A80 below Areq introduced variability into the line and are one cause of large WIP bubbles. Additionally, tool areas with predicted capacity shortfalls for future factory load levels were prioritized. While these prioritization approaches make sense and were based
on data, the type of approach – AM, PM, or WE – to be used to improve the area was based on gut feel.

In addition to metrics tracked for overall factory performance, the mX Steering Committee with input from the mX Group has started tracking some additional metrics. Those metrics include the M-Ratio and the Coefficient of Variation (CoV) of Availability. The M-Ratio is the ratio of scheduled to unscheduled maintenance. An M-Ratio of 9 is considered world class by Intel (Fearing, 2006). The CoV is a normalized calculation that enables the user of the data to compare the width of various probability distributions. The CoV of Availability calculation is shown below.

\[ CoV_{Availability} = \frac{\sigma_{Availability}}{\mu_{Availability}} \]

Where $\sigma_{Availability}$ is the standard deviation and $\mu_{Availability}$ is the average of the most recent 91 days of availability data. While use of these metrics represents a move in the right direction, namely driving desired behavior, there is a disconnect between what is desired – zero throughput variation – and what is measured – schedule to unscheduled maintenance or the variability of availability. These metrics implicitly assume that a single factor drives variation.

Take the M-Ratio for example. Assume a given tool set has an observed M-Ratio of 0.5. Intel has identified an M-Ratio of 9 as world class. Viewing the M-Ratio, even in conjunction with availability and utilization metrics, one might assume that this tool needs to be refurbished and maintenance procedures need to be improved. However, if the tool is down only 1% of the time and is not a constraint tool, the odds are that unscheduled downtime is not driving throughput variability.

The CoV of Availability has a similar problem. Assume that all tools in an area have an aggregate CoV of Availability of 0.06. Standing alone, this level of capacity variation may appear to be acceptable. However, the propagation of throughput variation is more a
function of the interaction between capacity variation and WIP arrival variation. A CoV of Availability of 0.06 may be sufficient for a tool with 50% excess capacity but completely unacceptable for a constraint tool with zero excess capacity.

One potential result of using either the M-Ratio or CoV of Availability is that organizational improvement efforts can be misallocated. For example, Tool Z may have a CoV of Availability of 0.08 and tool X may have a CoV of Availability of 0.06. Based strictly on CoV of Availability, tool Z would be prioritized over tool X even though tool Z may have 100% excess capacity while tool X has no excess capacity.

To better understand the source of throughput variation, a more balanced approach is needed. One method is to start with a simple throughput model of wafers out of a tool as a function of beginning on hand inventory and WIP arrivals at the tool. By doing so, variation in WIP flow can be eliminated as a potential source of throughput variation.

### 5.2 Measures to Identify Throughput Variability

Throughput is a function of many different variables. Figure 12 shows the variables involved in most manufacturing processes (Gershwin, 1994).

As the model suggests, throughput variability is caused by four variables, WIP arrivals to an operation, beginning on hand inventory at the operation, people capability to process available WIP, and finally equipment capacity. The current method for understanding throughput does not take all of these variables into account. To address the shortfalls of the existing metrics and indicators, the following analytical technique was developed. The technique has two goals. First, it should provide an easy to understand and interpret
measures of performance. And second, it should provide a high level indication of the most probable source of throughput variation in an area.

The analysis approach starts with a throughput model of outs from an operation as a function of WIP arrivals to and beginning on hand inventory at a given tool area. A simple linear regression of aggregate arrivals to and beginning on hand inventory at versus outs from a tool area, is modeled using the equation,

\[ P_t = \alpha + \beta Q_t + \gamma A_t, \]  

where \( P_t \) denotes production outs in day \( t \), \( Q_t \) denotes the beginning on-hand (BOH) in day \( t \), \( A_t \) denotes arrivals in day \( t \), and \( \alpha, \beta, \gamma \) are regression coefficients. For the purposes of the model, we assume that all tools can process all arrivals. For example, a select tool area may consist of 7 separate manufacturing tools and process five different operations, all of which may have different arrival rates. (Note: This assumption is generally acceptable at most tool types in the fab. There are areas, such as lithography, where tool dedications violate the aggregate assumption. While this variation analysis approach is still applicable to those areas, users should consider process flexibility or inflexibility as a potential source of variation.) Aggregate arrival, beginning on hand, and outs data are collected daily over a rolling 91 day period. This approach provides a “tool view” of the production environment and accounts for two of the four variables that may contribute to throughput variability, arrivals and beginning on hand inventory. Figure 13 provides an example of a tool area where throughput variation is entirely explained by daily arrivals to and beginning on hand inventory at an operation. Actual throughput is plotted on the y-axis versus predictions from the linear regression on the x-axis. (Note: Data has been normalized for confidentiality purposes.)
As mentioned above, the model is a simple least square fit of two explanatory variables, arrivals and beginning on hand inventory. One measure of fit of a regression model is a quantity known as R-Squared (RSq). If the model renders a high $R^2$, then most of the variability in production is attributable to either the variability in arrivals and/or in BOH. Throughput Model 1, shown in Figure 13, with an RSq of 0.96, provides a clear example of a toolset whose throughput is fully described by the model. This implies that variability at the tool level is not a critical issue for this toolset. Additionally, the model indicates that throughput can be predicted using the equation:

$$P_t = 0.012 + 1.11Q_t + 0.880A_t$$

| Term | Estimate | Std Error | t Ratio | Prob>|t| |
|------|----------|-----------|--------|------|
| $\alpha$ | 0.012 | 0.007689 | 1.56 | 0.1225 |
| $\beta$ | 1.111 | 0.094311 | 11.78 | <.0001 |
| $\gamma$ | 0.880 | 0.021401 | 41.13 | <.0001 |

Table 1: Throughput Model 1 Parameter Estimate Statistics

Here $\alpha$, $\beta$, and $\gamma$ refer to the regression coefficients shown in Equation 1.
If a high RSq is observed, then typically the regression coefficients are significant and can be used to understand and react to WIP dynamics at the tool. (Note: Table 1 above provides parameter statistics for Throughput Model 1 which shows that the coefficients are indeed significant.) For example, consider two extreme cases, Case 1 where $\gamma$ is near tol and Case 2 where $\gamma$ is near to 0.

**Case 1:**
When $\gamma$ is near to 1 daily production closely follows daily arrivals. Here the impact of the BOH on smoothing throughput variability is likely to be minimal. This is an ideal case, as there should be minimal WIP and the flow times through the operations are short.

**Case 2:**
When $\gamma$ is near to 0, daily production depends more on BOH and less on arrivals. Here $\beta$ acts as a smoothing parameter. The smaller $\beta$ is, the higher the expected WIP levels. In this case, there would be value from increasing the production capability at the tool set as well as from smoothing the arrivals.

If, however, a low RSq is observed, then the majority of the variability in production is not due to arrivals or to the BOH. Therefore, one of the other two variables identified in Figure 12, either Equipment Capacity or People Capability must be the source of throughput variation. In this case, focusing improvement efforts on reducing tool or people variability would be expected to be more beneficial than smoothing arrivals or manipulating BOH levels. Figure 14 below provides an example of where arrival and beginning on hand variation explains some but not all throughput variation.
The model proposes that throughput can be predicted using the equation:

\[ P_i = 0.134 + 0.285Q_i + 0.634A_i \]

The parameter estimate statistics indicate that the coefficients of the model are indeed significant, see Table 2.

| Term | Estimate | Std Error | t Ratio | Prob>|t| |
|------|----------|-----------|---------|----------|
| \( \alpha \) | 0.135 | 0.034 | 3.97 | 0.0001 |
| \( \beta \) | 0.285 | 0.064 | 4.43 | <.0001 |
| \( \gamma \) | 0.635 | 0.069 | 9.25 | <.0001 |

**Table 2: Throughput Model 2 Parameter Estimate Statistics**

While the fit to the model is relatively good with an RSq of 0.60, the increased dispersion clearly points to the absence of a variable in the regression model. In this case, further investigation is required to understand the source of the increased variation. Figure 15 below provides an example of a poor fit, where either Equipment Capacity and/or People Capability is the source of throughput variation.
For Throughput Model 3, the model suggests that throughput can be predicted using the equation:

\[ P_i = 0.573 + 0.092Q_i + 0.353A_i \]

The parameter estimate statistics indicate that the coefficients of the model are indeed significant, see Table 3.

| Term | Estimate | Std Error | t Ratio | Prob>|t| |
|------|----------|-----------|---------|------|
| \( \alpha \) | 0.573 | 0.114 | 5.03 | <.0001 |
| \( \beta \) | 0.092 | 0.041 | 2.23 | 0.0284 |
| \( \gamma \) | 0.353 | 0.098 | 3.60 | 0.0005 |

Table 3: Throughput Model 3 Parameter Estimate Statistics

In the case of a low RSq, the regression model is not as predictive. Here, the regression coefficients values of \( \beta \), \( \gamma \) provide a gross indication of how much WIP is needed at the toolset, i.e. the smaller are the coefficients the greater the WIP levels at the operation.
While the discussion above has provided a means for interpreting the model, the question of prioritization of improvement efforts remain. It is recommended, that, for prioritization purposes, areas where the RSq is above 0.70, throughput variation can be attributed mostly to arrivals at the tool and can therefore be prioritized lower than areas with a lower RSq. For areas with an RSq less than 0.7, an additional level of detail is required. To that end, two questions need to be answered. First, at an average level, is there enough capacity? And second, what percentage of the total time are the area tools down?

The first question can be answered using the A80-Areq metric. However, a clearer, easier to communicate metric is the Capacity Ratio (Cap Ratio). The Cap Ratio is defined as the most recent 91 day average of area capacity divided by the most recent 91 day average of area arrivals. The second question can be answered by calculating the Downtime Ratio (DT Ratio). The DT Ratio is simply one minus daily percent available.

Areas with a large Cap Ratio and a low DT Ratio are less likely to have equipment issues as a source of throughput variation and should have throughput models with a high RSq. The throughput model shown in Figure 13 had DT Ratio of 0.07 and Cap Ratio of 2.75, which corresponds neatly to the observed RSq of 0.96. This is the optimal case for an operating area, lots of excess capacity with very little downtime. This area could be classified as a stable operating area in that throughput exiting the area does so in a stable predictable manner.

Areas with a large DT Ratio and Cap Ratio will tend to have a fit that falls in between these extremes. The throughput model shown in Figure 14 has an observed RSq of 0.60 and corresponding Cap Ratio and DT Ratio of 2.1 and 0.16 respectively. This is an example of an area where a good deal, but not all of the observed throughput variation can be attributed to arrival variation. While the Cap Ratio indicates the presence of plenty of excess capacity, the DT Ratio indicates that total downtime may be a contributing factor to throughput variation.
Areas with a large DT Ratio and small Cap Ratio are likely to a poor throughput model fit. The throughput model shown in Figure 15 has an observed DT Ratio of 0.14 and Cap Ratio of 1. This is an example where arrivals and BOH, while significant, explain very little in terms of throughput variation. Here the low Cap Ratio and the high DT Ratio indicates that equipment performance is a driving factor.

Once the DT and Cap Ratios have been calculated, the M-Ratio and CoV of Availability can be used to identify or eliminate tool performance as a source of throughput variability. Figure 16 below contains the corresponding metrics for the three areas described above.

<table>
<thead>
<tr>
<th></th>
<th>DT Ratio</th>
<th>M-Ratio</th>
<th>COV Cap</th>
<th>Cap Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 1</td>
<td>0.07</td>
<td>0.63</td>
<td>0.08</td>
<td>2.76</td>
</tr>
<tr>
<td>Model 2</td>
<td>0.16</td>
<td>0.40</td>
<td>0.15</td>
<td>2.1</td>
</tr>
<tr>
<td>Model 3</td>
<td>0.14</td>
<td>0.23</td>
<td>0.12</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 16: Complementary Equipment Metrics

As predicted by the throughput model and confirmed by the DT and Cap Ratios, the first throughput model is an area that does not require immediate attention of an improvement team. The second and third models, however, could use improvements in tool performance as evident by excessive downtime and a poor M-Ratio, see Figure 16 above. In this case, application of AM to the second and third model areas would be most appropriate.

**5.4 Visualizing the Data**

An additional tool useful in visualizing the interaction between equipment performance and WIP dynamics is the empirical probability or frequency distribution. By plotting the probability distribution of equipment capacity and WIP arrivals for a given area, managers and technicians can easily understand how their area is performing. Furthermore, the probability of failure on a daily basis can also be predicted. Figure 17 below shows the probability distribution that corresponds to the first throughput model shown in Figure 13.
As expected, the probability that arrivals at a given area will exceed the capacity of the area to process those arrivals is essentially zero. This implies that throughput variation is attributable to the variation of arrivals from upstream suppliers and outside the immediate control of managers and technician operating this area. This is not the case for Throughput Model 2. As shown in Figure 18 there is a non-zero probability that, on any given day, arrivals will exceed capacity.

The probability plot for arrivals and capacity for Throughput Model 2 clearly displays the interaction between capacity and arrival variation. Figure 19 displays the probability distributions for capacity and arrivals for Throughput Model 3. With a Cap Ratio of 1,
Figure 19 confirms that this is a constraint tool.

![Figure 19: Throughput Model 3 Arrivals and Capacity Probability Distributions](image)

Figure 19 highlights the critical nature of tool performance for a constraint tool. As predicted by the throughput model, throughput variation is caused by factors other than WIP dynamics. The DT and Cap Ratios, 0.14 and 1 respectively, indicate that tool performance may be an issue and that more information is needed. While the CoV of Availability is relatively high, 0.12 for a constraint tool, the M-Ratio of 0.23 indicates that unscheduled down time may be the major source of throughput variation in this area. Figure 20 below provides a full description, the benefits, and drawbacks of the variation analysis indicators. The following section uses the variation analysis technique described above to prioritize area improvement efforts to areas that increase throughput variation.

<table>
<thead>
<tr>
<th>Variation Analysis Performance Indicators</th>
<th>Description</th>
<th>Benefits</th>
<th>Drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-Squared</td>
<td>Indicates the level of fit of a regression model.</td>
<td>Indicates whether TPT variability for a given tool is a function of WIP dynamics or area performance</td>
<td>This is an aggregate of all area manufacturing tools and all layers. Is not done to the operation level. Can be misleading as a stand alone metric.</td>
</tr>
<tr>
<td>DT Ratio</td>
<td>1- Daily Percent Available</td>
<td>Indication of tool health, similar to m-ratio but this based on total time</td>
<td>Does not give you an indication cause of downtime</td>
</tr>
<tr>
<td>Cap Ratio</td>
<td>Aggregate average capacity divided by aggregate average arrivals</td>
<td>Indicates the amount of room between arrivals and capacity</td>
<td>Does not give you an indication of what is impacting tool performance</td>
</tr>
<tr>
<td>M-Ratio</td>
<td>Ratio of scheduled to unscheduled downtime</td>
<td>Indication of tool stability/tool health.</td>
<td>Can be misleading. Need to also look at down time percentage or tool availability.</td>
</tr>
<tr>
<td>CoV of Availability</td>
<td>Coefficient of variability for availability</td>
<td>Normalized measure unlike A80 or required availability.</td>
<td>Need to look at this metric in combination with M-Ratio and Cap Ratio. More difficult for people to understand.</td>
</tr>
</tbody>
</table>

Figure 20: Variation Analysis Performance Indicators
5.5 Analysis of Thin Films 2

Thin Films 2 is a two of a kind tool that processes one operation in the process flow. (Two of a kind tool is defined as a tool type of which there are only two of in the entire factory.) To understand the source of throughput variation in this operation, a model of outs as a function of arrivals to and beginning on hand inventory at this tool set was created, see Figure 21 below.

![Thin Films 2 Throughput Model](image)

Figure 21: Thin Films 2 Throughput Model

The fit to the model is exceptionally good with an RSq of 0.99. This indicates that throughput variation at this operation is a function of WIP dynamics and not equipment or people performance in the area. The equipment performance metrics, shown in Figure 22, confirms this finding.

<table>
<thead>
<tr>
<th>DT Ratio</th>
<th>M-Ratio</th>
<th>COV Cap</th>
<th>Cap Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.09</td>
<td>1.7</td>
<td>0.15</td>
<td>15.8</td>
</tr>
</tbody>
</table>

Figure 22: Thin Films 2 Equipment Performance Metrics

To further emphasize the point, Figure 23 shows the arrival and capacity probability distributions for this operation. Note there is a zero probability that arrivals at this
operation will exceed capacity on any given day. Because it is clear that throughput variation at this operation is a function of arrivals to this operation, two courses of action can be taken. First, identify the upstream tool area that is the source of variation. This can be accomplished by generating a throughput model for each of the previous operations successively until the tool area is found. From there, the source of throughput variation can be identified by analyzing tool performance and directly observing work in the area.

Second, throughput variation can be reduced by either decreasing the variation of arrivals through active WIP management based on the indications provided by the regression coefficients, \( \beta \) and \( \gamma \).

5.6 Analysis of Thin Films 3

Thin Films 3 is another two of a kind tool that is also used only in one operation in the process flow. To understand the source of throughput variation in this operation, a model of outs as a function of arrivals to and beginning on hand inventory at this tool set was created, see Figure 24 below.
As evident by the model’s poor fit, RSq is equal to 0.35, throughput variation is not completely explained by arrival and beginning on hand variation. The Cap Ratio for Thin Films 3 is quite large at 18.3 indicating that there is more than sufficient capacity in the tool area to process incoming WIP. The DT Ratio, however, is rather large at 0.39. Going a step further, the M-Ratio, at 0.33, indicates unscheduled downtime is the potential cause of throughput variation in this area. Figure 25 provides a summary of the equipment performance metrics.

<table>
<thead>
<tr>
<th>DT Ratio</th>
<th>M-Ratio</th>
<th>COV Cap</th>
<th>Cap Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.39</td>
<td>0.33</td>
<td>0.38</td>
<td>18.3</td>
</tr>
</tbody>
</table>

Figure 25: Thin Films 3 Equipment Performance Metrics

Figure 26 confirms the indications of the equipment performance metrics. As shown below there is a non-zero probability that arrivals will exceed the area’s capacity to process those arrivals.
This area is a prime candidate for equipment improvement efforts. Autonomous Manufacturing would prove useful as unscheduled downtime appears to be the cause of both the excessive DT Ratio and CoV of Availability. The next step in analysis would be to go to the point of activity and engage the area technicians to confirm the analytical findings.

5.7 Analysis of Etch 3

The analysis of Etch 3 will demonstrate the importance of direct observation in the analysis process. Etch 3 consists of two tools that runs one operation in the process flow. Figure 27 shows the throughput model for Etch 3. As evident by the model’s low RSq, 0.20, throughput variation in this area is not attributable to WIP dynamics.
Etch 3 has a Cap Ratio that indicates sufficient capacity on an average basis. The distribution of Capacity is relatively narrow which indicates minimal to zero interactions between arrivals and capacity. The DT Ratio indicates a large percentage of downtime. While a large percentage of downtime can be concerning, the M-Ratio indicates equipment performance really should not be an issue in this area. Figure 28 below summarizes the equipment performance metrics.

```
<table>
<thead>
<tr>
<th>DT Ratio</th>
<th>M-Ratio</th>
<th>COV Cap</th>
<th>Cap Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.14</td>
<td>4.0</td>
<td>0.06</td>
<td>15.6</td>
</tr>
</tbody>
</table>
```

The probability distribution for Etch 3 clearly supports this point. Figure 29 below shows the large amount of excess capacity in this area. Additionally, the variation of arrivals and daily capacity do not interact. The summation of these metrics indicates that direct observation of the area is required to understand the source of throughput variation in this segment of the line. Direct observation of the area shows that lots are held at this operation as a WIP or line management policy.
Throughput variation in this area points to variation of another downstream operation that requires operations to be held at Etch 3. Waste Elimination efforts could be applied to downstream segment of the process to eliminate the non-value added waiting time experience in this section.

5.8 Conclusions

The variation analysis approach begins by modeling outs as a function of beginning on hand inventory and arrivals at an operation. This model acts as a first pass screen to differentiate areas that are stable, where WIP flow is a function of arrivals and beginning on hand inventory, from areas that are not. For areas that are not stable, i.e. fit to the model is low, further investigation is required. The next step in the approach is to eliminate equipment performance as a source of throughput variation. The DT Ratio and Cap Ratio coupled with the M-Ratio and the CoV of Availability assist in ruling out or confirming equipment performance as the most likely source of throughput variation. Finally, a period of direct observation in the area of interest is used to confirm the findings of the analysis and to understand the impact of people capability to do work in the area.

This approach is applicable for first pass analysis of area performance. It can be used by Intel in two ways. First, as a prioritization tool, this approach acts as a decision support
tool to area managers deciding on the types of operational improvements any given area should work on. This will eliminate wasted effort improving activities that have little to no impact on an area’s future performance. Second, this approach can be used to provide general performance feedback to areas of the factory. Areas with a high RSq can be classified as stable with predictable work flows while areas with low RSq can be classified as unstable with unpredictable work flows. Use of this approach will provide a clear, easy to interpret definition of a stable tool in the factory, a goal all areas should be working for.
Chapter 6: Observations and Recommendations

F17 has accomplished quite a bit since beginning their lean transformation in early 2003. They have committed to lean as a factory staff. They have formed an infrastructure to develop training content. They have developed and delivered hundreds of hours of training content. They have led improvement activities that have realized tangible results in direct labor savings, decreased safety incidents, and decreased quality events. Moving forward, F17’s biggest challenges will be focusing their organizational efforts and engaging middle management as the sustaining engine for mX. The following section discusses observations from the six month LFM Internship. Recommendations based on those observations provide potential next steps for the mX implementation.

6.1 Observation 1: Fragmented Organizational Effort

Intel fabs are busy places. F17 is no exception. Standard WIP management, equipment health, safety, and quality concerns keep all stakeholders occupied for more hours than available on a given day. Couple this fact with various improvement initiatives and daily work quickly becomes unmanageable.

In their current state, F17, on top of normal manufacturing requirements, is pursuing many activities that have factory wide visibility. Ranking among those initiatives are the ramp in production volume, the mX initiative focused on eight tools in the factory, High Precision Maintenance focused on developing the “Perfect PM”, as well as other cycle time reduction and quality initiatives led by various groups. The proliferation of initiatives, specifically improvement initiatives has led to the formation of teams that compete for resources to achieve similar or identical goals.

For example, many of the GLOM’s involved in mX equipment improvement efforts also have equipment teams and/or High Precision Maintenance teams working to answer the same question – how do we, as a team, improve equipment performance. Every team approaches the problem in a different manner. The mX teams begin with inspection to restore the tool to new or better condition while upskilling the work force. The HPM
teams have described an ideal state of the Perfect PM and have begun their work by making maintenance actions easier to understand and execute. While both approaches intend to reach the same goal – zero breakdown maintenance and minimal equipment downtime – they take very different paths to get there. Additionally each of these teams generally requires membership of some of the same people. This leads to the excessive use of a very valuable resource, human capital.

To address this, it is recommended that leverage points between initiatives be identified. For example, the Perfect PM that HPM teams are working toward meshes nicely with the AM/PM work already developed by the mX Group, in fact the Perfect PM is also the ideal state for mX, see Figure 30 below.

![Figure 30: Perfect PM Journey](image)

Every GLOM at F17 currently has an mX team focused on improving operations in their tool areas as well as an HPM team working to define the “Perfect PM”. Assuming each area is allotting the same amount of effort to both the mX and HPM initiatives,
consolidating the efforts will double the available human capacity and focus the energy of all team members on the common goal. Additionally, considerable work has been accomplished by the mX group in the development of a means for vetting and a mechanism for resolving equipment related improvements. Consolidating the efforts under a single initiative will decrease the frustration associated with developing training content and an improvement roadmap required by newer initiatives. Additionally, use of the variation analysis tool presented in Chapter 5 can further focus organization effort by assisting in the identification of throughput variation.

6.2 Observation 2: Continuous Improvement at All Levels

Many companies have a traditional distribution of work between management and direct labor. Intel is no exception. In a traditional model, levels of management are involved with improvement activities while direct labor executes the routine work of manufacturing. Problems that occur in the organization are identified and resolved by management. The solutions are then handed down to the frontline workforce for implementation. The motto of this type of organization is “This is your problem and this is how you fix it.” Figure 31 (Shiba & Walden, 2001) provides a visual interpretation of this model.

![Diagram of traditional distribution of work organizational chart]

Figure 31: Traditional Distribution of Work Organizational Chart
(Note: I represents the improvement activities that management are generally responsible for and R represents the routine work that frontline labor is generally responsible for.)

From 1998 until 2003 this structure has worked for F17 because the competitive environment was unchanged. Intel’s “Company Optimization System,” – first to market
with new technology – was unchanging because it was designed to meet an unchanging need of the economic environment, faster processor clock speed. Figure 32 (Shiba & Walden, 2001) shows a simple model explaining this system.

Based on their current technology roadmap, F17 will continue to compete in the commoditized chipset market segment in the near term. To be successful, they cannot utilize the old company optimization system. F17 has recognized this and is attempting to make the change at an organizational level from the one shown in Figure 31 to the organization shown below in Figure 33 (Shiba & Walden, 2001).

In this model all levels of the organization are responsible for some portion of routine as well as improvement work. Improvement work takes place at the point of activity by the experts in the process. Management facilitates this process by enabling solutions to be developed and implemented. The motto of this type of organization is “What is the problem and how can I help?” This shift in organizational models transforms the
Company Optimization System from a single function, process development for Intel, to organizational learning. The rate of learning then becomes the source of competitive advantage for fabs such as F17.

The mX initiative has started this transformation; however, the current path may not lead to sustainable change. In their book, Four Practical Revolutions in Management, Shoji Shiba and David Walden outline four principles for managing that may assist in improving the sustainability. These principles are:

- Practice systematic development of skills
- Treat management as a coherent system
- Focus on people and their purposes
- Integrate best practices

Based on direct observation and application of these principles, over the course of the internship, the following recommendations are made:

- Transition the role of the mX Implementation Team Members from driver to mentor/coach
- Leverage the existing organizational structure
- Develop a system for teaching the mX principles at all levels of the organization.

As mentioned in Chapter 3, the mX Implementation Team has been responsible for leading mX activities in designated areas of the factory. While this has been a good model for the early stages of content development, it will not provide the organization with an incentive to assume future responsibility (Flinchbaugh, 2006). The current implementation model follows the process outlined below:

- mX Group develops training content
- mX Group delivers content and leads a group through activities
- Next Steps are developed following the completion of activities
- mX Implementation Team Member insures Next Steps are closed

This cycle is then repeated. The intent of this model is to teach by doing. However it has two severe drawbacks. First, while it has led to some quantifiable successes, this model teaches a process or series of tasks by which to resolve specific problems, i.e. excessive breakdown maintenance, excessive direct labor requirements, etc. It does nothing to teach frontline management or labor the manner in which to think about problems. And second, it does not provide the members of the teams with a sense of ownership of the process. Proof of these two points has been directly observed through interactions with various members of mX teams. Participants continuously refer to work facilitated by the mX group as mX activities, which are viewed by the organization as additional work and not a way to approach existing work. By making the management, both process engineers as well as operations managers, responsible for delivering the training and managing the follow through an incentive to fully understand the thought process will be provided.

The recommendation for management to lead implementation activities is often met with the reality that these members of the organization do not have the time to execute effectively. This is entirely true given the existing organizational structures. As described in Chapter 3, cross functional teams (FACM, GLOMs, MOD Teams) are gathered together to work on issues that relate to area performance, see Figure 4. As a result of past mX activity, a parallel structure has been created in the formation of mX tool teams, see Figure 5. The mX tool teams and the MOD Teams have very similar attendance. By leveraging the existing organizational structure two critical things are accomplished. First, excess meetings can be minimized. And second, those organizations have leadership relationships that are fairly well developed. Instructing those leaders in systems of thinking behind the structured improvement processes that have been developed offers great potential for sustained implementation.
To support this shift of leadership responsibilities, the new responsibilities of management should be made clear. No longer will it be the leader’s responsibility to solve the problems with the system. Rather, the leader should be responsible for understanding the system’s dynamics and teaching the rules and principles of mX thinking at the point of activity with the people doing the work (Spear, 1999). A mental model of this type of behavior was developed (diagramed in Figure 35 below) through the course of the internship and tested across several improvement teams. This model was applied to develop Plan, Do, Check, Act problem solving skills with manufacturing technicians.

![Diagram](image)

**Figure 35: Mental Model for Systematic Skill Development**

The first step of the process, Step A, is to develop a deep understanding of the current as well as the ideal state of the system being improved. For the leader, this understanding can be developed from past experience or from direct observation of the system in question. From this understanding, it is the leader’s responsibility to ask several key questions (Spear, 1999):

- How do you do this work?
- How do you know you are doing this work correctly?
- How do you know that the outcome is free of defects?
What do you do if you have a problem?

Asking these questions will assist the area leader in directing the people doing the work to self-conclusion in the gaps of the existing system. Additionally, it will highlight to the leader the key failure modes that should be addressed in the first step of the problem solving process.

Once high agreement on the source of the problem has been developed, a plan to resolve the problem can be generated. Step B, provides the leader with the opportunity to ask questions to identify the activities, connections, and flows of the current system and clearly understand how the improvement plan addresses the shortcomings of the old system. Additionally, the scope of the plan should be addressed at this point to ensure it is manageable as well as in the sphere of influence of the group solving the problem. Step B provides a key opportunity for the leader to reinforce the rules of mX.

Step C, the next interaction of the mental model, involves directly observing the execution of the plan. As execution represents the application of knowledge, this step presents the leader with the opportunity to understand the effectiveness of the teaching and the points of both success and failure to be highlighted in the after action review of the next step.

Finally, in Step D, the leader can help direct the learning of the group by ensuring the after action review is framed in terms of activities, connections, and flows. The after action review serves two purposes for the leader. First it provides an opportunity to reinforce the common language through discussion of the rules and principles of mX. Second, it provides the leader with the opportunity to understand future development opportunities of the people in the system, i.e. person A needs to develop root cause analysis skills, person B needs to develop process mapping skills, etc.
6.3 Future Areas of Research

While conducting the research several salient questions arise that may be a source for future research topics in this area. First, as mentioned in section 3.2, it is unclear what role manufacturing flexibility decisions play or can in decreasing, increasing, or minimizing throughput variation in a semiconductor manufacturing environment. Opinions vary greatly on this subject, but are mostly contained to qualitative, experience based assessment of area performance. Increased flexibility carries an associated capacity cost due to test and qualification requirements of manufacturing equipment. Decreased flexibility carries an associated cost of potentially long queues at individual machines while other tools of similar capability are starved. A systematic method for determining manufacturing flexibility would prove useful to Intel because it could minimize the loss of capacity while minimizing the resulting increase in throughput variability.

The second area that appeared interesting from a research point of view, was the potential benefit of flow simplification in a semiconductor factory. In the current state, products go through approximately 400 process steps throughout the manufacturing process, often through the same series of operations multiple times. To ease the management of this process, all product exiting a given operation enters a single queue to be processed on one of any number tools available for that process. This results in a huge number of flow paths products can take to get from raw material through to Sort and E-Test. Simplified flows may lead a decrease in the probability for error leading to more efficient WIP management by enabling the shift of management responsibility from operational area to manufacturing layer. This may involve some amount of dedication and therefore may not be applicable to all areas. To this end, the potential benefits of flow simplification would have to be weighed against the costs of decreased manufacturing flexibility.

Finally, in retrospect, it would have been useful to have a more detailed knowledge of the methods used to diagnose, coordinate, and improve manufacturing operations. To this point, the following course materials, while not taken, were used throughout the research process and are recommended for individuals pursuing similar areas of research: 2.852 –
6.4 Conclusions

The implementation to date has developed some much needed momentum. However, there are still some critical challenges ahead. First, application of this variation analysis tool will assist managers in prioritizing the type of improvement work to be done in an area. Second, focusing organizational effort to a single initiative will reduce organizational confusion and increase the effectiveness of teams currently in progress. Finally, engagement of frontline management is the key to the sustainability of the mX effort. By transitioning implementation responsibilities to the leaders in the existing organization and developing a system to educate and support those leaders, a unique organizational capability can be created at F17.
References


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