92

Aligning Tool Set Metrics For Operation In A Multi Technology High Mix Low Volume Manufacturing Environment

By

Alyson B. Naughton

Bachelors of Science in Manufacturing Engineering, Worcester Polytechnic Institute
(1997)

Submitted to the Department of Mechanical Engineering and the
Sloan School of Management
In Partial Fulfillment of the Requirements for the Degrees of

Master of Business Administration
Master of Science in Mechanical Engineering

In Conjunction with the Leaders for Manufacturing Program at the
Massachusetts Institute of Technology
June 2005

Signature of Author____________________________________
May 6, 2005
Sloan School of Management
Department of Mechanical Engineering

Certified by____________________________________
Roy E. Welsch, Thesis Advisor
Professor of Statistics and Management Science

Certified by____________________________
Daniel Whitney, Thesis Advisor
Senior Lecturer, MIT Engineering Systems Division

Accepted by____________________________
David Capodilupo
Executive Director of Masters Program
Sloan School of Management

Accepted by____________________________
Lallit Anand
Chairman, Committee on Graduate Studies
Department of Mechanical Engineering

This page is intentionally left blank

Aligning Tool Set Metrics For Operation In A Multi Technology High Mix Low Volume Manufacturing Environment

By

Alyson B. Naughton

Submitted to Sloan School of Management and the Department of Mechanical Engineering on May 6, 2005 in partial fulfillment of the requirement for the Degrees of

Master of Business Administration
Master of Science in Mechanical Engineering

Abstract

Ireland Fab Operations (IFO) is transitioning and leading the way within Intel to Multi-Technology High Mix Low Volume (MT-HMLV) manufacturing. To avoid errors in estimating metrics, specific capacity tool set metrics for this manufacturing environment now need to be considered. Approximations for high volume manufacturing may be far enough from MT-HMLV realities that company revenue is affected by making delivery commitments that can not be met. The Intel Model of Record (MOR) which is used to determine the number of each tool set needed to produce a given volume of product does not consider MT-HMLV realities. Things such as product change-overs, cross qualified tools, and smaller than 'normal' lot sizes can create chaos on the manufacturing floor that has not been traditionally accounted for.

Thesis Supervisor: Roy E Welsch
Title: Professor of Statistics and Management Science

Thesis Supervisor: Daniel Whitney
Title: Senior Lecturer, MIT Engineering Systems Division

This page is intentionally left blank

Acknowledgements

I would like to thank Intel Corporation for their support of the Leaders for Manufacturing Program. For all of the help once I arrived and throughout my stay in Ireland: Steve McKenna for getting me to Ireland in the first place; Kenneth Daly for guiding my research and not letting me get stressed out too much; Alan O'Donovan for helping work through the simulation models and providing support in getting the information I needed to run them; the rest of the IFO ME group for taking me in as part of your group and making me feel a little more Irish.

Thanks to my family for all the encouragement they have given me throughout time at LFM.

Most importantly, thanks to my husband, Jim, who knows how responsible he is for any success I achieve.

Bendacht For Cech N-Oen Legfas.

This page is intentionally left blank

TABLE OF CONTENTS

List of Figures

This page intentionally left blank

Chapter 1: Introduction: Intel Corporation and Ireland Fab Operations (IFO) Background

This introductory chapter provides background information on Intel Corporation and its manufacturing facility located in County Kildare, Ireland. The research conducted for this thesis was conducted in Kildare at the part of the site known as Ireland Fab Operations (IFO). Also included is an overview of the thesis structure.

1.1 Problem Statement

Intel Corporation has traditionally been a high volume manufacturer. Recently they have been transitioning some of their facilities to High Mix Low Volume (HMLV) manufacturing. Ireland Fab Operations is Intel's premier HMLV fab. Because of this, many new manufacturing problems and issues are surfacing at IFO that have not yet received visibility at other Intel facilities. The aim of this thesis was to address one of these issues and aid IFO in their transition to HMLV. In this effort, a tool capacity planning study was conducted that demonstrates the difference between Intel's current capacity planning metrics and the capacity the equipment at IFO has been able to achieve. This thesis provides the background information for the study as well as discussing the methodology and results and providing suggestions for IFO as they move forward.

1.2 Intel Corporation

Gordon Moore and Bob Noyce co-founded Intel Corporation in July of 1968. From 1968 to 1971 they operated at as a memory company. In 1971 Intel released the first microprocessor. As of this point forward they have been an industry leader in the manufacture and supply of chips, boards, and semiconductor components to the computer and communications industries. In 2005 Intel currently employs more than 78,000 people in over 48 nations worldwide working at 11 fabrication facilities and six assembly and test facilities. All of these employees are working towards Intel's mission “to be the preeminent building block supplier to the worldwide internet economy” (www.intel.com). A look at their 2003 geographic breakdown of revenues shows just how global Intel has become (see Figure 1 below).

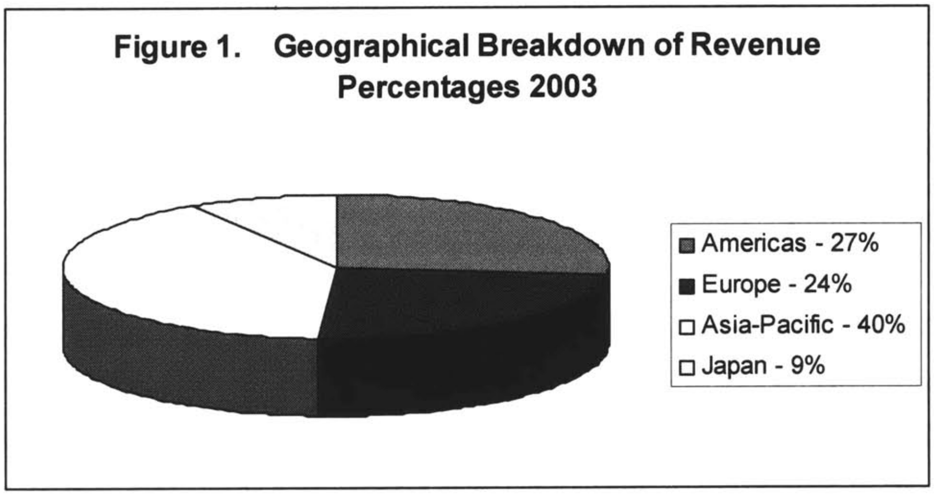


Figure 1 Geographical Breakdown of Revenue Percentages 2003 (www.intel.com)

1.2.1 Moore’s Law

In 1965 Gordon Moore, co-founder of Intel Corporation was able to forecast the rapid growth of technology innovation in the semiconductor industry. He stated that the densities of transistors on integrated circuits will double every couple of years. As this statement became true, the term ‘Moore’s Law’ was coined to explain the relationship. Figure 2 below shows the evidence of Moore’s Law from 1965 to beyond 2000.

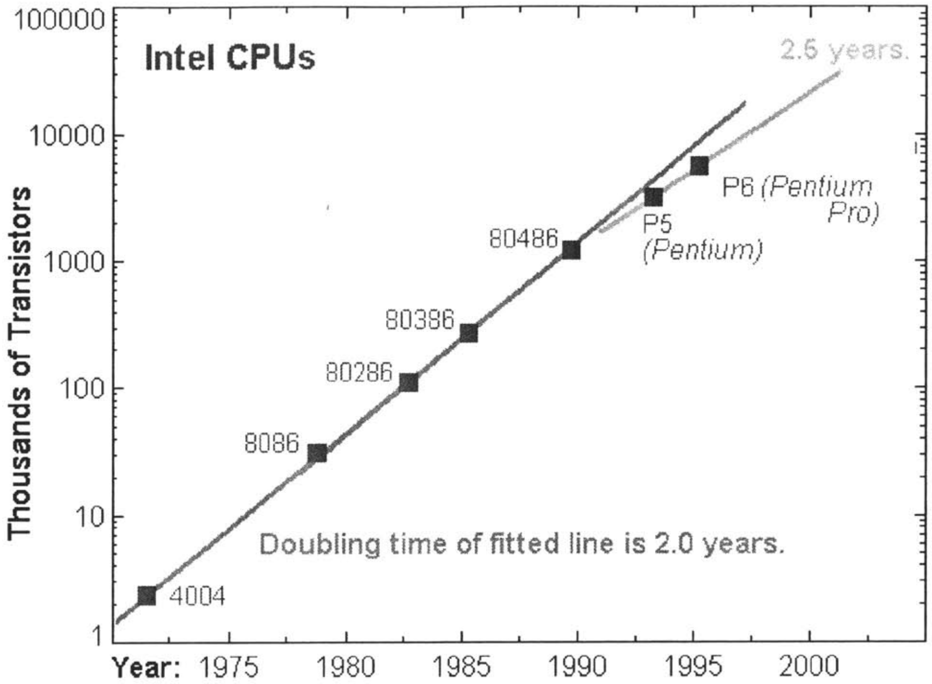


Figure 2 Moore's Law (http://www.physics.udel.edu)

While Moore himself argues that the establishment of the law itself could lead to a self-fulfilling policy (Killian, 2003), the phenomenon has kept pace for nearly 40 years (www.intel.com). Further, many agree that currently there is no end in site and that although the semiconductor industry may ultimately fail to keep pace with Moore's Law there is no agreement on when this may occur. People at Intel are going to extreme measures to assure they keep pace with Moore's Law. In fact, their website currently states the following: "The key to ensuring that Moore's Law continues is that the transistor itself must evolve from the planar (flat) structure generally used today. Many new ideas have been proposed to solve the evolving issues. One radical proposal currently being studied involves a three-dimensional, tri-gate transistor. These new transistors achieve higher performance with greater power efficiency than traditional planar transistors, and are designed such that they can continue to be scaled down while being reasonably simple to manufacture (www.intel.com)."

Gordon Moore has been quoted as saying the following about Moore's Law: "Moore's law is a term that got applied to a curve I plotted in the mid-sixties showing the increase in complexity of integrated circuits versus time. It's been expanded to include a lot more than that, and I'm happy to take credit for all of it" (www.pbs.org). This shows how one man's 1965 predictions are shaping the strategy of Intel still today and will continue to in the future. This phenomenon will be discussed in more detail in the section on cultural design in Chapter 6.

1.2.2 Intel Products and Customers

The following table, Figure 3, organizes information from Intel's website showing the products they currently produce.

PCs and Enterprise Systems:
Microchips used in high-performance and value desktop and mobile PCs, PC tablets, and entry-level to high-end servers and workstations
Chipsets, which perform the essential logic functions surrounding the CPU, for computers, servers and workstations
Motherboards, which combine Intel microprocessors and chipsets to form the key subsystem of a PC or server
Networking and Communications:
Microchips used in the systems that transmit and direct traffic across the Internet and corporate networks
Networking devices and equipment that provide access to the Internet, local area networks and home networks
Hardware and software for integrated voice and data networks
Wireless networking products for home and business
Hardware components for high-speed, high-capacity optical networks
Embedded control microchips designed to perform specific functions in devices such as laser printers, factory floor automation instruments, cellular phone base stations, and network communications hubs, routers and switches
Wireless Communications and Computing:
Applications processors, which process data functions such as calendar and email programs, for wireless handheld devices and cellular phones
Baseband chipsets, which enable voice communication functions, for wireless handheld devices and cellular phones
Flash memory, which retains data when a device's power is turned off

Figure 3 Principle Products and Services (www.intel.com)

The increasing number of products being produced creates operating challenges for Intel. This fact provides the basis for the existence of this research and thesis concerning tool capacity planning in a High Mix Low Volume (HMLV) environment at Intel's Ireland Fab Operations.

The bulk of current Intel customers are Original Equipment Manufacturers (OEMs) such as Dell Inc. and Hewlett-Packard who in 2003 together purchased over 30% of Intel products by sales dollar volume. Other Intel customers are handheld computing device, network communications equipment and cellular handset OEMs as well as several small and large businesses and individual users (Pandolfo, 2004).

1.2.3 Historical Competitive Advantage

Historically Intel has dominated the semiconductor market by being the first to market with technological advances. They have been able to accomplish this through a strong dedication to R&D. For example, in 2003 Intel invested nearly $4.4 billion in R&D and $3.7 billion on capital investments with a total of $30 billion in net revenue. Over 25% of revenue dollars going to R&D and capital investment shows Intel's huge growth rate and dedication to developing new products and processes.

In addition to creating value for their company through large investments in R&D, Intel has a noteworthy strategy for deploying information and executing their strategy at their widespread global sites. This strategy is known as 'Copy Exactly!', CE! for short, and is implemented through their network known as the 'Virtual Factory', or the VF. CE! enables Intel to reduce their time to market by providing a framework for Intel to develop product and process technology simultaneously. The foundation of CE! Is a structured approach to the transferring of information and methods from their development sites to their production facilities. Intel disseminates this information through their factory network, or VF, which consists of several teams from global sites sharing and spreading knowledge towards the goal of standardization and the use of best known methods (BKM). Put together, CE! and the VF provide Intel with higher yields and shorter time to market than many of the other players in the same market.

1.3 Ireland Fab Operations (IFO)

In 1990 Intel began production at Collinstown Industrial Park in Leixlip, County Kildare, Ireland. Initially the 360 acre site operated as an assembly and test facility and in 1993, they completed their first wafer production factory in Ireland, Fab 10. Once Fab 14 was completed on the site shortly after, the two fabs were joined to create Ireland Fab Operations or 'IFO' as they are commonly known today. IFO consists of over 150,000 square feet of cleanroom space and currently employs over 2,200 workers (Pandolfo, 2004). In June of 2004 Intel officially opened Fab 24, Intel's first 24mm facility outside of the US, adjacent to IFO. In total Intel has invested over $5 billion and employs over 4,000 people in Ireland.

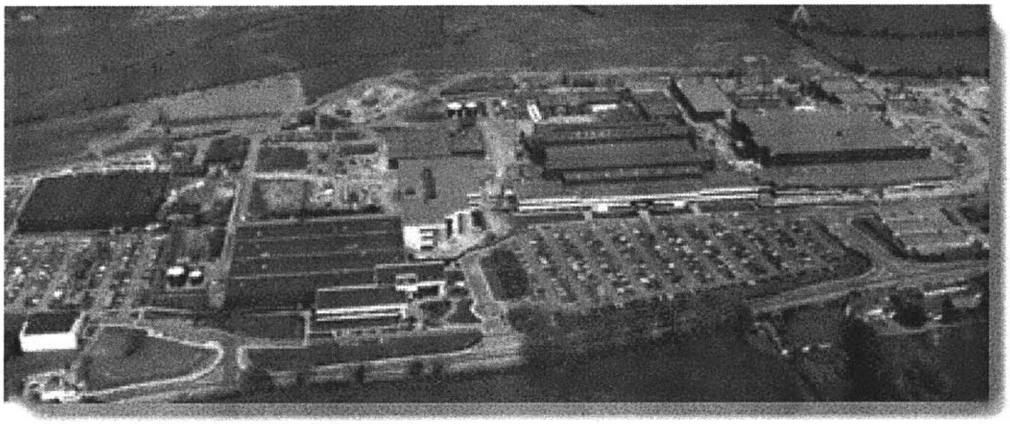


Figure 4 Intel Ireland Limited, Leixlip, County Kildare, Ireland (www.intel.com)

1.4 Thesis Structure

This thesis is structured into seven remaining chapters. Chapter 2 discusses general manufacturing principles and those used by Intel. Chapters 3 and 4 provide information on High Mix Low Volume (HMLV) manufacturing and capacity planning for manufacturing environments as well as providing research on capacity planning for a HMLV environment. Chapter 5 shows how discreet event simulation was used as a case study to illustrate the gap between Intel's current capacity planning methodologies and those required by a HMLV setting. Organizational, strategic, and cultural barriers to transitioning to a HMLV manufacturing state are provided in Chapter 6. Lastly, Chapter 7 provides recommendations for IFO as they continue to move towards HMLV and closing thoughts on the effect of HMLV on semiconductor manufacturing.

Chapter 2: Manufacturing Principles

This chapter will provide background information on historical and current manufacturing principles and discusses how Intel has evolved through their use of several principles over time. It serves as a basis for Chapter 3 which will show the transition to High Mix Low Volume (HMLV) manufacturing occurring in several industries and markets today.

2.1 History of Manufacturing

Before the 20th century most manufacturing consisted of skilled laborers and craftsmen. However, many acknowledge Henry Ford for changing this with his creation of the Model T assembly line. Ford's Model T assembly line was focused on keeping costs as low as possible. In this vain he strove for standardization and the famous 'any color as long as it's black' quote was born. In fact, this was the direction the manufacturing industry was headed, a focus on cost cutting at the price of customization—everything was becoming standardized. The consistency of the manufacturing process drove efficiencies which saved money. The amount of money saved by Ford brought the mass produced automobile to the general public and the manufacturing industry was changed forever.

One major way Ford revolutionized the manufacturing industry with his assembly line was the shift in skills required by his employees. Instead of needing several skilled craftsmen to assemble a single car, he was able to hire unskilled workers to perform specific tasks. The skilled workforce shrunk and became the designers, engineers, and decision makers of the firm. This split in the workforce has continued to plague several manufacturing firms with problems even today. Eventually success was achieved in the manufacturing industry by those who could best bridge the gap between these two workforces and in the late 20th century those best at doing this were the Japanese.

After WWII the Japanese embraced Dr. W. Edward Deming who is widely credited with revolutionizing the quality of Japanese manufacturing strategy. He did this by making quality, not cost, the major driver of Japanese manufacturing. Very quickly the quality of Japanese manufactured goods provided them a competitive advantage over other firms. Eventually, they took this quality advantage, combined it with economies of scale for an increasing number of product variations and developed leadership in High Mix Low Volume (HMLV) manufacturing.

Many struggles are still realized by today's manufacturing firms. Some firms are still trying to implement their initial phase of Japanese quality methodologies. Others are working towards continuous improvement of these philosophies. Still, other firms are working to implement mass customization—the highest form of HMLV. How each of these firms implements their manufacturing strategy depends on the production system they are using and what they are trying to achieve with their system. The next section provides background information on production systems and how they have evolved over time.

2.2 Production Systems

All production systems can be categorized into two main types: those driven by process and those driven by product. Each company needs to pick the driver that best matches the strategy they are trying to achieve. For example, a system based on product may enable a firm to produce large quantities of non-differentiated goods at a low cost while a system focused on process may allow a firm to make several different versions of similar products and alter the volumes of these products they are producing as demand varies. This section will provide brief descriptions of several production systems and how they fit into each of these frameworks.

2.2.1 Production System Descriptions

In 1995 John Miltenburg expanded upon the product/process matrix developed by Robert Hayes and Steven Wheelwright in 1979. Miltenburg's matrix can be seen in figure 5 below (Miltenburg 1995). This section provides the basis for understanding their matrix in order to develop a background for Chapter 3: High Mix Low Volume Manufacturing. Basic knowledge of the principles of each system will enable the reader to realize the inherent challenges in HMLV manufacturing.

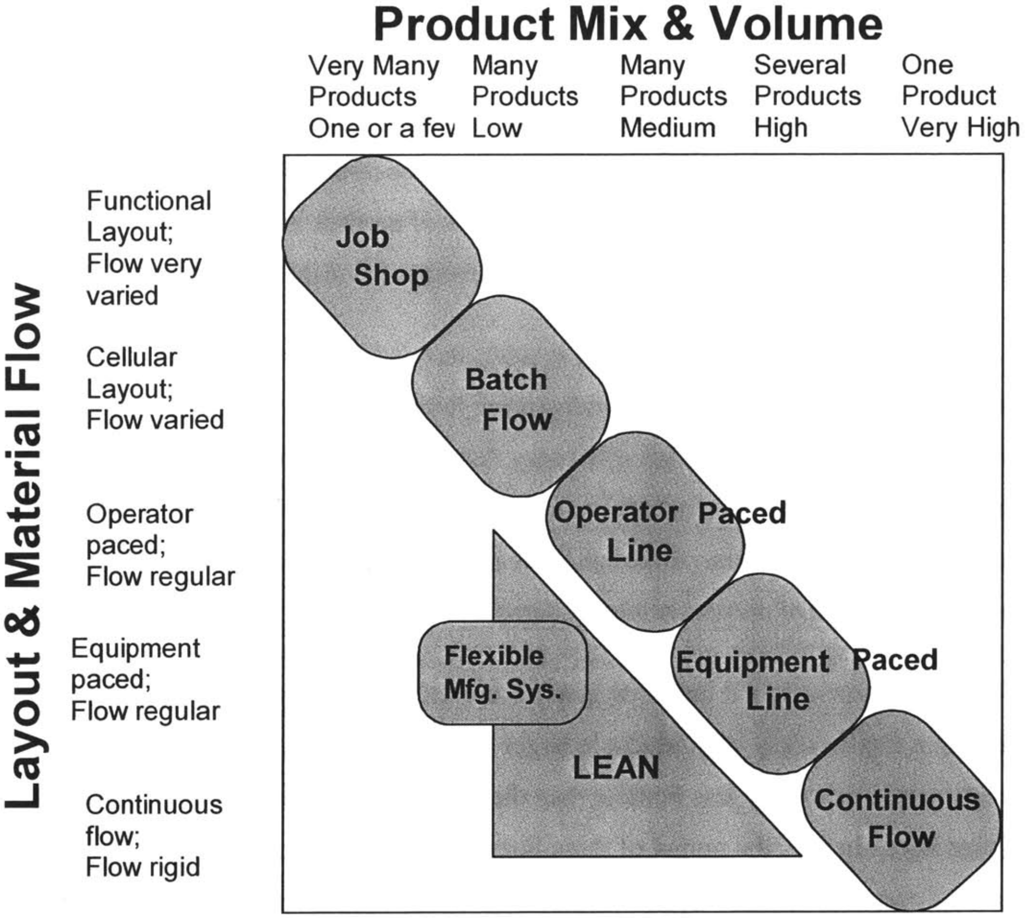


Figure 5 Updated Hayes/Wheelwright Product/Process Matrix by Miltenburg (Miltenberg, 1995)

The smallest volumes of products are traditionally manufactured in a job shop environment which is product driven. Job shops produce several product varieties in volumes from one to a few. Pieces flow through the manufacturing line in varied ways with a functional layout. This means that several departments or workstations consist of general purpose equipment that is used by highly skilled workers that typically cannot perform all of the operations necessary to manufacture the product. Each department or workstation is responsible for a specific task that is essential to manufacture, but typically no one person or workstation is responsible for the product from start to finish.

Batch flow manufacturing systems are slightly more standardized than job shops but are still considered product driven systems. In a batch flow system fewer products are produced in larger volumes than in a job shop. However, the layout is usually still very modular with several departments or workstations, each responsible for specific tasks but not the entire manufacturing process. The flow of product is in batches or lots that stay together as a group as they move through the manufacturing process.

Operator-paced line flow manufacturing systems have slightly higher volumes that batch flow systems and consist of manufacturing lines dedicated to a single product or product family. These systems are often very flexible and their output is influenced and controlled by the number of workers on the line and the amount of teamwork undertaken by these workers. Although these systems are product driven, they are approaching the line of process driven systems.

Similarly, equipment-paced line flow systems are dedicated manufacturing lines producing a small variety of products in larger volumes than in a batch flow system. These systems are usually less flexible than the operator-paced lines but often produce at higher rates. In fact, the output of these lines is set by the speed of the line and the success of operator interaction or teamwork is often minimized as compared to an operator-paced line. As is true for operator-paced manufacturing systems, equipment-paced lines are on the cusp between product and process focused manufacturing systems, however, equipment-paced lines stand just over the line on the process focused side.

Continuous flow manufacturing lines typically produce one product at very high volumes and are process based systems. These systems usually have a high degree of automation and a low level of variation, the product is standardized for the purpose of little operator intervention and therefore low costs. Often these systems are the most costly to set up due to high capital equipment costs of automated machines, but high product volume is usually able to absorb these costs.

Lean manufacturing systems, with their development credited to the post WWII Japanese manufacturing era, are made up of a collection of manufacturing principles. These include: total quality management (TQM), 5S, Just-in-Time (JIT), statistical process control (SPC), kaizen, waste elimination, pull production, and high levels of standardization. Lean manufacturing is typically used for manufacturing lines producing several products or product variations in medium to low volumes. Several companies are implementing various aspects of lean manufacturing to meet their needs. It is important to recognize that each principle can provide benefits in different ways to different situations—a company needs to evaluate which of the principles to implement in each situation. Because of the different ways each company implements lean principles, a lean system can be product or process focused. However, most lean principles drive at improving the process of manufacturing and its effect on the product flow.

Finally, Miltenburg discusses Flexible Manufacturing Systems (FMS) which fill a specific niche of manufacturing needs. FMS systems consist of computer controlled machines linked by automated material delivery systems. Once this highly capital intensive system is set up there is little or no need for operator intervention in the manufacturing process. These systems are typically used for highly specialized low volume products and are process based.

As many market segments are being driven by customer demand for customization of products, many companies operating with each of the above mentioned manufacturing systems are looking to make their operations more flexible. In order to do so effectively a company must realize the benefits and limitations of their current system. Miltenburg's model provides a basis for this that companies should consider when making product and process changes to their manufacturing systems.

2.3 Production and Capacity Planning

Production and capacity planning are main drivers behind customer satisfaction. Production planning effects when and how products are built—it is often considered the 'production schedule'. Firms use several methods to determine this schedule which is often determined by their manufacturing strategy. Capacity planning involves determining the number and type of machine a company installs at a facility to meet manufacturing demand. Because capacity is often determined based on an expected demand—the more complicated the tooling is for the process, the further in advance these decisions are made—determining the desired level of output for a line and making sure it meets customer demand is often difficult. In some cases demand must be forecast one year or more in advance of production in order to get the necessary tooling, training, and testing in place to manufacture a product. Accordingly, capacity planning is at the top of manufacturing firm's list of critical impacts to their manufacturing strategy. This section provides background information on production planning as well as a brief introduction to capacity planning which is discussed in more detail in Chapter 4.

2.3.1 Production Planning

Production planning is the method that factories use to determine when to produce which products and at what volume. These decisions are influenced by the manufacturing system in place at a facility, product volumes, product lead time, and expected demand. The method a company chooses will have an impact on their flexibility, cost, and quality. Depending on company focus, a push, pull, or push-pull combination system may be used.

A push production system is typically based on a long term forecast and is driven by a Material Replenishment System (MRP). Push production systems typically have higher levels of inventory and Work In Process (WIP) and are characterized by high equipment utilization. The main drawback of push production systems are high inventory costs and low flexibility. Because these systems often manufacture to stock and not to order they carry the risk of building obsolete products.

Pull production systems are usually based on customer demand which has a shorter forecast. Lower levels of inventory and WIP exist as product is not introduced into the line unless a machine is ready to process it. As demand is realized, it is communicated through the line from the end to the start in a way such that material will not be waiting for a machine to be available to process it. Pull production systems usually utilize lean manufacturing principles such as JIT and Kanban to manage their inventory and supplies to further reduce costs.

A push-pull system production system combines the two methods to optimize the overall manufacturing process. A line may start out as a push system and end as a pull to reduce the amount of high inventory dollar WIP. Or, a line may build identical product in a push system up until the point the product becomes differentiated at which point the line switches to a pull system based on customer demand. This method is referred to as postponement. The combination of these two systems often works best for complex products or products with several and varied manufacturing process steps.

2.3.2 Capacity Planning

Chapter 4 is dedicated to the topic of capacity planning. This section serves as a general overview of how capacity planning relates to manufacturing strategy and introduces key topics that will be discussed in further detail in Chapter 4.

As mentioned above, capacity planning is often a decision made based on expected customer demand well in advance of actual production. Because this process can be so complicated several studies and schools of thought exist on how to accomplish capacity planning best. These include the trade off between general use vs. dedicated equipment, bottleneck management or the theory of constraints, and analyzing 'factory physics'. Factory Physics is the term coined by Wallace J. Hopp and Mark L. Spearman used to describe a methodology for analyzing the underlying behavior of manufacturing systems (Hopp and Spearman, 2001). Each of these topics will be discussed in detail in Chapter 4.

A firm's manufacturing strategy will have an effect on how they approach capacity planning. The more expensive and complicated the equipment, the more precise a firm needs to be. For instance, a manufacturing system with high capital equipment can be unprofitable if their machines are not utilized well. On the other hand, not having the capacity available to meet demand can also be very costly as a company could loose customers to a competitor that can meet demand. Managing the correct amount of equipment between these two fine lines can be difficult, especially if demand forecasts are poor. Capacity planning is typically easier in a highly labor intensive manufacturing environment as people are often quicker to train than machines are to build and offer flexibility by being able to perform multiple tasks.

2.4 Intel's Practices

Intel began as a high volume mass production firm. Over time this is changing as industry pressure is developing the need for differentiated products in several market segments. As a high volume mass production firm, Intel typically based manufacturing strategy decisions around the high utilization of their extremely high cost capital equipment—they are process focused with a push production system designed to force maximum utilization of their equipment. These machines are not getting any less expensive; they are being put to a new level of stresses, and are causing new problems for manufacturing engineering groups within Intel. In addition to manufacturing capacity planning, production planning issues are also arising. For example, demand is becoming more difficult to forecast and this in turn is causing equipment decisions to be put off and become even more complicated.

Intel has begun to focus on these issues and many employees are trying to find ways to determine capacity and production volumes with uncertain demand. This is magnified in a High Mix Low Volume (HMLV) environment as equipment is often shared by several products. The next chapter will provide further information on how HMLV is affecting the manufacturing industry and specifically how Intel is being affected.

This page intentionally left blank

Chapter 3: High Mix Low Volume Manufacturing

There is an increasing pressure on many manufacturers to produce customized and varied products. This fact, coupled with uncertain and changing product demand creates new issues for high volume manufacturers such as Intel. This chapter will discuss the evolution of and challenges presented by high mix low volume manufacturing.

3.1 High Mix Low Volume Drivers

As discussed in Chapter 2, the evolution of focusing on High Mix Low Volume (HMLV) manufacturing began in Japan after WWII. Ever since the 1960's the Japanese have been the world "leaders in incorporating economies of scale to increased product mix" (Killian, 2003). Many manufacturers in the United States are still playing catch up but some have gained ground and are becoming competitive through their use of manufacturing systems based on those originally developed in Japan. Today, customers are demanding more and more customization of products and are moving away from commodity type goods to more highly specialized items. This shift is pushing manufacturers further towards HMLV and is making HMLV manufacturing issues a more important focus of operations teams at many companies.

The push for differentiated products is occurring in all industries from industrial equipment to consumer goods such as automobiles, running shoes, and even clothing. Each of these industries feels the pressure to move towards HMLV manufacturing directly from their customers as well as from their competitors. In many cases companies are being forced to customize products or lose business. Because of this, several companies are switching to HMLV environments without drastically changing their manufacturing strategy. This causes a lag between the process they are currently using and the process they should be using in their new environment. The next section discusses some of the impacts HMLV is having on the manufacturing operations at companies and some of the factors that companies should consider as they shift their manufacturing to a HMLV environment.

3.2 Impact of High Mix Low Volume on Manufacturing Operations

R. Michael Mahoney's book entitled "High-Mix, Low-Volume Manufacturing" is widely recognized as one of the most comprehensive books about HMLV manufacturing. In his book, Mahoney stresses the importance of companies finding the balance between the factors of cost and mix. Figure 6 shows the total cost curve as it is related to product cost and product mix.

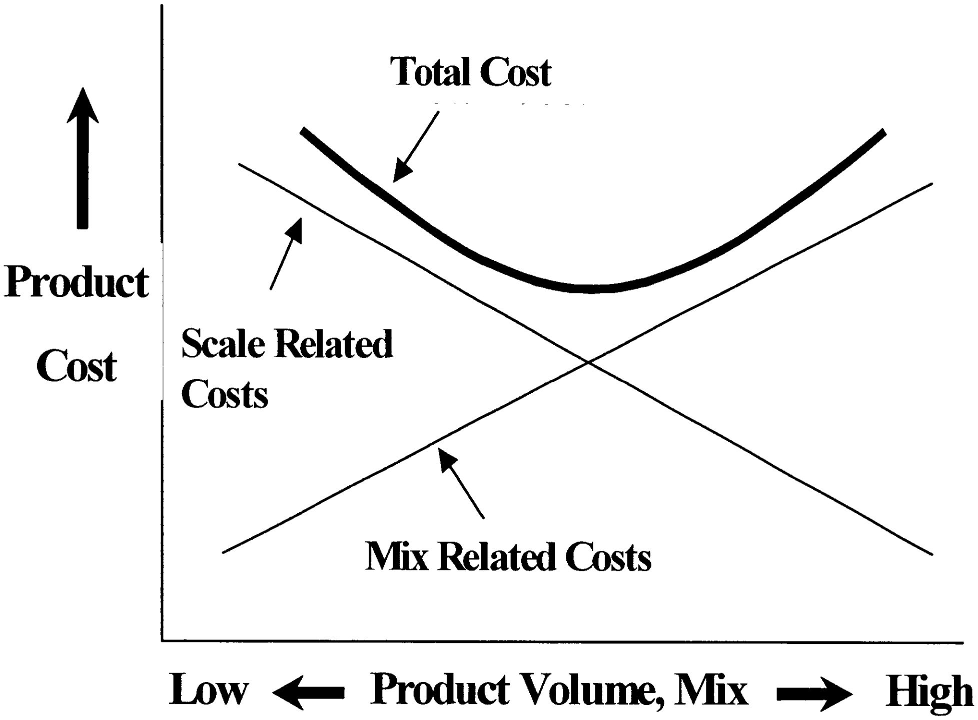


Figure 6. Graphical Depiction of Balance Between Product Mix and Cost (Mahoney, 1997).

This graph shows that as the number of customers and products increase, the total cost initially decreases, until economies of scale are realized, and then increases as the inefficiencies of producing several varied products is realized. So, for many companies that are transitioning to HMLV where economies of scale were initially realized and optimized now face an operating environment where the costs associated with offering a wide mix of products is negating the effects they previously achieved. This presents not only a change in the economics of manufacturing but also in the mindset of employees and the goals the company should be striving to achieve.

Inevitably, as a company transitions to HMLV numerous challenges will arise that will push their total cost curve higher. These complications include the need for increased staffing levels and training, multiple and frequent machine set ups, increased metric needs, and more frequent product qualifications. All of these issues present obstacles that a company was not previously dealing with in the same way before they transitioned to a HMLV environment. The introduction to new problems is an issue in itself but the need to view the problems from a HMLV viewpoint is also difficult for a company to realize.

3.2.1 Common HMLV Operating Issues and How They Impact Operations

The greater demand for new product introductions clearly creates the need to increase product qualifications and testing. However, it also presents the need for more highly skilled employees that have the ability to adapt quickly and multi-task. These employees will also require more training throughout their career as new products are introduced more often. Frequent new product introductions also create the demand for the development of new metrics and product specifications.

High product mix in a manufacturing environment also leads to an increase in the number of metrics and the frequency that things are measured. Usually, higher product mix at similar volumes requires higher staffing levels than the same volume with little or no mix. Also, increased machine set ups and product changeovers places new stresses on a workforce that may not be quick to adapt to their new working conditions.

Machine utilization can be greatly effected by HMLV manufacturing. For instance, it is often difficult to maintain the same high utilization once frequent product changeovers are introduced. Further, frequent changeovers and set ups can often lead to the need for more frequent and varied preventative maintenance requirements. Lastly, HMLV commonly causes less than optimal batch sizes that can also have a significant effect on machine utilization. This is especially true with many of the semiconductor processes at Intel that exploit a machine cascade efficiency to achieve their utilization rates. A machine is considered exploiting a cascade efficiency if all wafers in a lot after the first one are started in the machine before the first one has finished processing. Therefore, the second wafer is loaded as the first is being processed and the overall throughput time for subsequent wafers (after the first) will be less.

In many cases, as mentioned above, these changes initially go unnoticed and unplanned for in a company until they are operating out of control or close to it. Some companies do not initially realize that their focus needs to shift from high capacity utilization to high equipment flexibility (Pandolfo, 2004). This change also requires a shift from focusing on producing volume to focusing on specific order fulfillment as each individual customer order becomes visible to the manufacturing line.

3.2.2 Common Responses to HMLV Operating Issues

Several suggestions exist on how to mitigate the risks involved with transitioning to a HMLV manufacturing environment. Chapter 6 of this thesis will discuss in detail some of the organizational changes required for a successful transition and continued operation. This section will briefly discuss some of the more tactical methods known to date that alleviate many of the issues presented by HMLV manufacturing.

In order to reduce the 'disruptions' HMLV causes to a manufacturing environment a company needs to find a way to make these 'disruptions' part of normal operating procedure. One way of doing this is moving to a single piece flow strictly pull based operation. This however is not feasible for many operating environments, many at Intel included, where existing machine set ups do not allow for one piece flow. However, all companies can benefit from moving the push-pull boundary to the extent their equipment allows. A second technique that can be used is differentiation postponement.

This is where a manufacturer will make a standard product that can be customized further on in the manufacturing process. The further down the manufacturing line the differentiation occurs, the more it is 'postponed'. This technique works well for manufacturers of many consumer goods such as color dyed clothing and building materials that are cut to size per each customer order.

Changes in process metrics can also alleviate some of the issues brought on by HMLV manufacturing. For instance, optimizing line flow and equipment for smaller lot sizes can reduce the time seen as wasted when smaller than optimal lot sizes are routinely being processed. Reducing set up times between product changes will have a similar impact on equipment utilization. Improving product forecasting can also be beneficial; however, reduced forecasting ability often comes hand in hand with an HMLV environment.

The following section will discuss in detail how Ireland Fab Operations is transitioning to an HMLV manufacturing environment and the problems and solutions to date that they have experienced.

3.3 History and Development of High Mix Low Volume at Ireland Fab Operations

As early as 2002 managers at Ireland Fab Operations (IFO) began organizing teams to facilitate their transition to HMLV manufacturing. Because IFO was built for high volume batch process flow manufacturing, several considerations were made to determine how best to transition to HMLV while remaining competitive and meeting their current metrics. Figure 7 below shows a 2002 start and prediction of their transition to HMLV by demonstrating the growth in the number of products they will manufacture at low volumes.

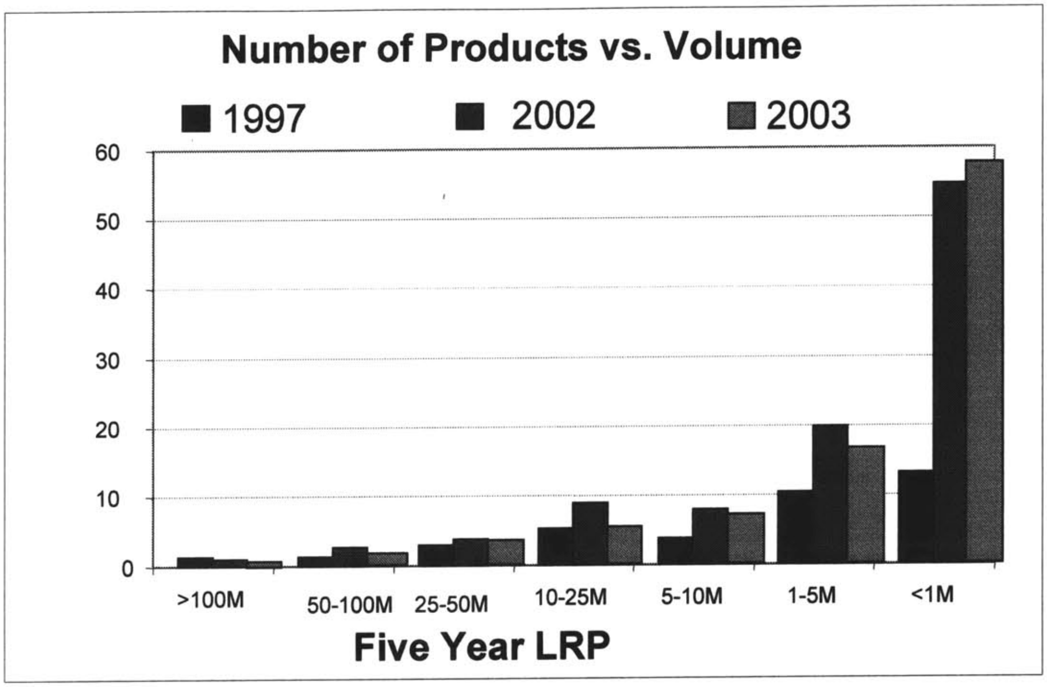
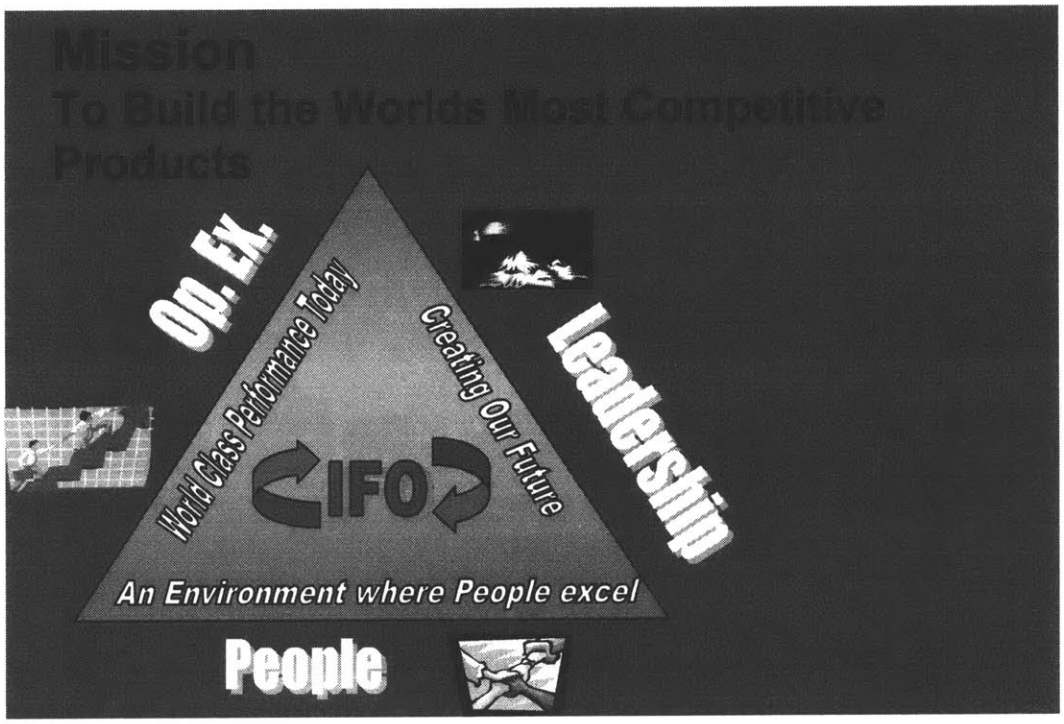


Figure 7. IFO Long Range Plan 2002 (Kelly, 2003)

Figure 7 shows an adaptation of IFO's Long Range Plan (LRP) for product mix and volume. In 1997 fewer than 35 products were manufactured. The 2002 forecast for 2003 predicted over 85 products and most of them would be made in small volumes of less than 1M each. This shift led IFO's management team to create workgroups focused on managing the transition going forward. This section will discuss the work done by these teams to date and the achievements they have made.

3.3.1 Management Review Committee Established to Address HMLV Issues

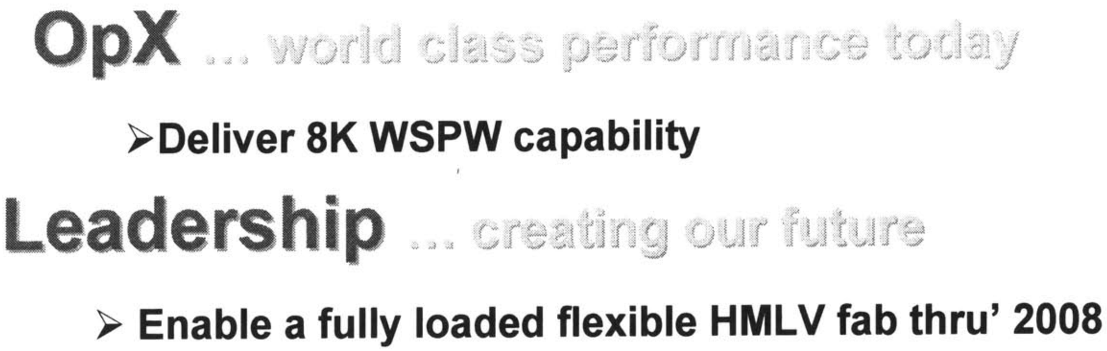
In early 2003 a Management Review Committee (MRC) was created to focus on HMLV issues. This team consisted of high level managers from Planning, Sort, Manufacturing Engineering, Yield Engineering, and Integration Engineering (IEN) (Pandolfo, 2004). Members of each of these groups are committed to a common fab-wide mission. Figure 8 represents this mission as communicated to employees and displayed throughout the factory for 2004.



Mission
To Build the Worlds Most Competitive Products

Figure 8. IFO 2004 Mission (www.intel.com)

HMLV priority is contained within the framework of this mission in both the Operational Excellence and Leadership portions as shown through detailed excerpts below.



OpX ... world class performance today

➢**Deliver 8K WSPW capability**

Leadership ... creating our future

➢ **Enable a fully loaded flexible HMLV fab thru' 2008**

Figure 9. Excerpt from IFO Objectives (www.intel.com)

With this mission and objectives focused on HMLV transition work groups have been established and have been working on several projects to further smooth the transition to HMLV manufacturing. The following section will discuss some of the efforts of these teams to date.

3.3.2 OpX HMLV Activities at IFO

Towards the end of 2003 a study was conducted by the MRC to determine what gaps existed in current manufacturing processes that may impede a transition to HMLV. This became an iterative process and was named 'OpX'. Their method consists of the following steps:

1. Educate Organisation on HMLV Change Transition and Key Success Metrics
2. Identify Changes by Department, Group and Individual and Perform Gap Analysis
3. Organise key Tactical and Break-thru Projects and Systems to meet HMLV Challenges
4. Manage Completion of Projects and Measure Success Indicators

(Adapted from Pandolfo, 2004)

The last three steps in this process are iterative and are continuously evolving.

Using the method above the following achievements have been accomplished:

- Standardized HMLV language throughout the fab and empowerment of the work group tasked with managing the transition.
- Product and process flexibility projects aimed at cross qualification of tools have created a dynamic environment where many products run on shared pieces of equipment.
- Automated Process Control (APC) has been implemented on several tool sets to enable a quick response to product change overs and set ups as well as to identify problem tool sets.
- Establishment of formal New Product Introduction (NPI) teams to handle the increase in the number of new products disrupting the manufacturing process.
- Skip lot exploitation to allow a reduction in in-process testing and a software program to facilitate inspection rates. For detailed information see the 2004 LFM thesis by Christopher Pandolfo entitled "Optimization of In-line Semiconductor Measurement Rates: Balancing Cost and Risk in a High Mix, Low Volume Environment"
- A scheduling management tool to comprehend and coordinate the complexities of multiple products was developed to analyze and monitor the manufacturing process. This gives an output of manufacturing options for given amounts of volume and variation. It considers equipment utilization, throughput time and demand variation and presents implementation recommendations as well as monitoring tools to support its users.

3.3.3 Future Priorities for OpX and HMLV Transition Teams

Currently the OpX teams at IFO are working on several projects to aid their transition to HMLV manufacturing. These projects are generally focused on cycle time reduction to facilitate increased volumes at quicker rates. The research project discussed in this thesis which aims to show the gap that exists between current capacity planning methods and those needed for HMLV is also included in the current OpX ongoing project list.

This page intentionally left blank

Chapter 4: Capacity Planning and Management

This section will provide an overview of current capacity planning strategies. There is also a section on how capacity planning is affected by HMLV manufacturing followed by one discussing how Intel is currently planning capacity for their wafer fabs and how this is affecting IFOs transition to HMLV manufacturing.

4.1 Traditional Capacity Planning Methods

Capacity planning strategies vary depending on the type of manufacturing process. For example, highly labor intensive processes with little expertise required can vary their capacity quickly and inexpensively while capital equipment intensive processes are often difficult to alter. However, it should be noted that many of the same general principles apply for all volumes and levels of operator vs. equipment intensity.

Another factor, the difference between dedicated and shared, or general use, equipment is important in capacity planning. If equipment is dedicated, it is generally highly specialized and cannot easily be adapted to process other products. If equipment can be easily shared, or is for general use, it is normally easily adaptable and can adapt to several machine set ups. The type of equipment used in a manufacturing environment will directly relate to its flexibility and how complicated capacity planning is. Section 4.2 will discuss in more detail the complexity introduced by high mix low volume to shared or general use equipment.

Differences exist in capacity planning and utilization for the short and long term. Short term capacity planning is often associated with Eliyahu Goldratt's Theory of Constraints which is discussed in Section 4.1.1 below. Long term capacity planning is often more complicated and often involves more people in a factory as it is when large capital expenditures are made. Several guidelines for determining long term capacity exist from simple equipment throughput time calculations to complicated modeling using a technique described by Wallace J. Hopps and Mark L. Spearman called

"Factory Physics". Section 4.1.2 will provide a brief overview of some of the theory presented in Hopps and Speaman's book "Factory Physics".

The following section will provide brief overviews of a few of the most generally used and respected methods of capacity management today. The Theory of Constraints and Factory Physics will be summarized.

4.1.1 Theory Of Constraints (ToC)

Eliyahu M. Goldratt book "The Goal" demonstrates the theory of constraints by telling the story of a factory manager. The premise of his philosophy is that 'The strength of any chain is dependent upon its weakest link' (Goldratt, 1984). Basically, anything that limits factory performance relative to the goal of making money is defined as a constraint by Goldratt (Goldratt, 1984). He contends that managing this constraint, setting all of the equipment in the line to constantly feed the constraint, and continuously managing this if there is a moving constraint, will optimize factory output. There are five general steps involved in ToC as follows:

1. Identify the System's constraints.
2. Decide how to exploit the system's constraints.
3. Subordinate everything else to the above decision. (Step 2)
4. Elevate the system's constraint.
5. If, in the previous step, a constraint has been broken, go back to step 1 but do not allow inertia to cause a new constraint

By following these five steps Goldratt contends that chaos will be reduced and optimal output of the line will be reached. Although this method is best suited for application to an existing manufacturing line, the theory can also be referenced when setting up a manufacturing system.

4.1.2 Factory Physics

Wallace J. Hopp and Mark L. Spearman, in their book “Factory Physics”, argue that a factory can benefit from being examined as a traditional science problem with a set of basic equations. Their method for doing so provides a problem solving framework often used in science as well as mathematical models that can be applied to any factory environment. They also underscore the importance of intuition and iterating the process continuously. This section provides a brief overview of some of the basics of factory physics and how it is applied.

With factory physics it is important to use basic descriptive models to understand what is happening in a factory. Knowing the values for things such as throughput, cycle time, and rework amounts enable the user to better use prescriptive, or optimizing, models to more fully understand their system. Then, using this information and building on ToC they have determined the following guidelines:

Determine the values for the following variables:

1. Throughput (TH): average output per unit time
2. Capacity: upper limit on TH
3. Cycle time (CT): the amount of time a part spends as WIP
4. Utilization: the fraction of time a workstation is not idle for lack of parts
5. Bottleneck Rate (rb): the rate of the workstation that has the highest long-term utilization
6. Raw Process Time (To): the sum of the long-term average process times of each workstation in the line
7. Critical WIP (Wo): the WIP level at which with no variability a line achieves maximum throughput with minimum cycle time and Wo = rb*To can be used to determine the correct amount of WIP needed to optimize the system.
8. With this information the following statements can be made:

- The minimum cycle time for a given WIP level is given by either To or WIP/rb, whichever is GREATER.
- The maximum throughput (THbest) for a given WIP level is given by rb or WIP/To, whichever is LESS.

Factory Physics continues on to provide more complicated models for determining the optimal capacity amounts by focusing on queuing theory within the system and reducing the variability in the system. Following the method of Factory Physics is a continuous improvement effort and is likely to show benefits such as reduced variability, increased worker understanding of the manufacturing process, and optimal capacity utilization.

4.2 Capacity Management for HMLV

Capacity planning for an HMLV environment can often be complicated. For instance, typically HMLV manufacturing systems have moving constraints that are rapidly and constantly changing. Further, changes in demand seen in HMLV environments complicate capacity management by always presenting a different situation to be managed which creates chaos and difficulty in constraint identification and management.

HMLV manufacturing systems often use shared equipment to process several products. Because of this there are additional set up and changeover times that need to be factored into the timing of the system. In addition, different products may have different processing times for the same piece of equipment. All of these factors combine to create a dynamic and constantly changing situation. Not only is product mix changing, but volume can vary, the demand horizon may shorten or lengthen, and increased maintenance may be required as a result of varying product mix.

When dealing with such a dynamic environment it is important for a company to have detailed methods for tracking and managing capacity utilization and optimization. For instance, a prioritization process needs to be put in place to determine which products take preference or which production steps should be more focused on than others. Also, the optimal amount to process before handling a changeover should also be determined. The higher the mix the more complicated these guidelines or rules need to be.

Following the guidelines of ToC, the products with the highest profit margin should always have preference. However, applying this rule to HMLV manufacturing is not realistic. Often, many companies are producing product mix because there are several products in their portfolio that have lower profit margins but allow the company to sell higher profit margin items. This is the case when customers demand a full product portfolio that includes older versions of products or when a company is responsible for replacement parts on older generations of their products. Without offering these lower profit margin items the customers could be lost. Because of this the importance of low profit margin items is not conveyed by their profit margin alone, but by what they contribute to the entire system. Following ToC's profit margin rule is not recommended for HMLV manufacturing. Determining priorities in an HMLV environment needs to be as dynamic as the process. The priorities can change daily or quicker and can have extremely dramatic impacts on the ability of the company to meet customer demand. Therefore, it is recommended that this be an iterative process for HMLV manufacturing.

When considering equipment sharing and the effect of equipment sharing on cost, Michael Porter believes the following:

> *If scale, learning, or the pattern of utilization are not important cost drivers, sharing is likely to raise costs……the costs of sharing will usually meant that sharing creates a disadvantage.*

(Porter, 1985).

Considering this, it is surprising that so many companies still use what they see as excess capacity for one product to build other products. However, it is important to note that in many cases firms do not set out to share equipment in this way but as time passes, demand changes, and new products are added while older products are maintained they often see this as a less expensive way to introduce new products. In the long term, it may be more sustainable to reduce capacity for each product individually as an alternative to sharing the capacity between the two products (Porter, 1985). Determining when to share and when to reduce capacity and then expand for a new product is one of the main challenges of a firm that transitions to HMLV from HVM. Chapter 6 will discuss some of the organizational barriers to seeing this issue clearly and will provide some recommendations to firms for avoiding this problem.

4.3 Intel Current Capacity Planning Methodology

Intel uses a combination of ToC and Factory Physics to plan capacity for their wafer fabs. Increasingly, Intel is turning to Factory Physics to enable them to reduce variation within their process and achieve higher equipment utilization rates. Capacity planning is a particular challenge at Intel because of the fact that semiconductor manufacturing is a highly re-entrant process with several tools processing parts many times throughout the manufacturing process. This section will briefly describe how Intel currently is conducting their capacity planning and how production is prioritized throughout their manufacturing line.

4.3.1 Model of Record (MOR)

Intel currently uses a tool, known as the Model of Record (MOR), to plan capacity for their facilities. This tool is set up for new technologies based on knowledge from previous technologies and lessons learned through processing past technologies at full volume in addition to the new technology in small volumes at development sites. The MOR is an Excel spreadsheet that provides the user with the number of pieces of a certain type of equipment needed for a given volume when it supplied the following information:

- Number of steps: how many times does the wafer get processed at this piece of equipment-a function of the re-entrant process of semi-conductor manufacturing.
- Required unit starts per week
- Goal utilization %: the tool is available, WIP is available to process, operator is present to run equipment
- Expected Availability %: tool is available to process WIP (excludes preventative maintenance, set ups, repairs)
- Protective Capacity (PC) amount: a buffer that is measured by the following equation where A = availability and U = utilization:
- $PC = (A-U) / U$
- EFL which is a yield measurement based on # of test wafers being run through the process
- Aggregate run rate: the average planned capacity
- Average rework amount
- Average sampling amount

When each of these above items is entered into the spreadsheet for each specific required tool, the quantity of that type of tool is provided. Of course, the spreadsheet is more complicated than described here, but this gives a general sense of the information being consulted and how equipment decisions are made.

Intel also has general rule of thumb equations that are used to approximate tool requirements. The following are 'rule of thumb' equations used by Intel to estimate the MOR calculations:

$$USC = (\text{Utilization} \times 168 \times \text{Run Rate}) / (\#\text{ Layers} \times \text{EFL} \times \text{Rework})$$

The above equation allows the estimation of the unit start capacity (USC) of a piece of equipment. It is used to determine how many wafers can be started on a piece of equipment on a weekly basis. It considers the planned utilization and the run rate of the equipment as well as the number of layers, a yield measurement (EFL) and an expected rework percentage.

A second equation used to estimate capacity needs at Intel is the 'Number of Tools equation'. This equation considers all of the information in the above equation as well as demand (ramp). The equation is as follows:

$$\# \text{Tools} = (\text{Ramp} \times \# \text{Layers} \times \text{Rework} \times \text{EFL}) / (168 \times \text{RunRate} \times \text{Utilization}).$$

This system contains several buffers and assumptions that highlight manufacturing issues for HMLV environments. For example, the MOR assumes a certain number of wafers for every lot and a certain number of lots for every batch. These HVM targets are increasingly difficult to achieve in an HMLV environment. Another example of this is rework amount. The MOR assumes all rework will occur at a certain number and not cause disruptions to the system by creating 'mini' lots being processed. Some of the assumptions made by the MOR affect high volume manufacturing as well as HMLV, however, in an HMLV environment these buffers are eroded by increased setups, changeovers, and machine maintenance and it is often difficult for IFO to meet the level of output being dictated by the MOR. In summary, the buffers are eroded by HMLV manufacturing and the best case scenario for which the MOR was created is no longer achievable. The challenge is to recover the eroded capacity through engineering and manufacturing projects.

Because the semiconductor manufacturing process requires extremely high capital intensive equipment that must be planned for months in advance of production, once the MOR is determined for a given technology it is extremely difficult to alter. Chapter 6 will discuss some of the organizational issues associated with the MOR and Chapter 7 offers some solutions to alleviate these issues.

4.3.2 Prioritization Process

Capacity management at IFO is complicated by their product mix and changing demand. To better utilize their equipment a lot prioritization system is employed that they 'dictates' which products should take precedence over others. This process is different for different pieces of equipment however; in general, the following guidelines apply as follows:

1. Run any lots designated as 'hot lots' or with special prioritization attached.
2. Pull forward up to ten lots of the same type to avoid changeovers.
3. Process remaining lots on a first-in, first-out basis to minimize throughput time.

These rules unfortunately do not match MOR assumptions. Further, because technicians actually make the decision which lots to run and when, these guidelines are not always followed. The basic premise that people perform to what they are measured against applies, and since each individual shift is measured on their throughput numbers, each shift tries to minimize changeovers occurring during their shift and will often pull more then ten lots ahead to avoid additional setups and changeovers. The difficulties encountered by this process will be discussed in further detail in Chapter 6.

This page intentionally left blank

Chapter 5: Discreet Event Simulation Demonstrates Current Capacity Planning Gap

Chapter 4 discussed capacity planning at Intel and introduced the Model of Record (MOR). Also, some initial difficulties IFO has with applying the MOR which originated for a high volume manufacturing environment to their HMLV environment were introduced. This Chapter will demonstrate how these difficulties have impacted IFO and will demonstrate the gap between MOR and actual at IFO by using Discreet Event Simulation.

As discussed in Chapter 4, the MOR is based on several assumptions and best case scenarios. At IFO, with their high mix and changing demand, they are never going to operate in the best case scenario. Also, all of the buffers inherent in the original MOR as it is created for high volume manufacturing, are slowly eroded by HMLV realities. These include small lot sizes, frequent changeovers, and increased equipment maintenance. Eventually enough of the buffer is eroded so that IFO is unable to meet expected metrics. Because HMLV is relatively new to Intel, these actualities are not fully comprehended or accounted for. This chapter will provide evidence of the erosion of the buffers and the impact HMLV is having on one particular tool set used at IFO.

5.1 Initial Approach

The focus of this project was to determine how operating in an HMLV manufacturing environment was impacting the MOR. Initially, the MOR was examined and an attempt was made to trace the source of the original information. Unfortunately this proved difficult as each MOR for a specific technology and toolset is built upon the MOR and best in class performance from the previous technology and the true source of the information is difficult to obtain. Chapter 6 will discuss some of the root causes for this difficulty. Because the MOR origins were not fully traceable to their fundamental level, project focus was narrowed to demonstrate the difference between MOR predicted throughput values and IFO HMLV reality.

5.2 Development of Models

With the purpose of demonstrating the gap between MOR predictions and current IFO realities discreet event simulations were created. Simul8 software was used as it was available through MIT and the author had previous course experience with the software package. One process technology and one tool set, a lithography stepper (NSJ) were selected to narrow the focus and allow for manageable results. This section will provide the basis for creating the models and state all of the assumptions made.

5.2.1 Creating the Process Flow and Baseline Model

The first step to creating the simulation models was to map the process flow of the NSJ equipment. At IFO there are four lithography steppers and each wafer is processed four different times by this tool set. Also, there are four products within the chosen product family that are processed by these four machines. Not all machines are qualified for all products. Figure 10 below shows the various levels of cross qualification for each tool and product.

	Product 1	Product 2	Product 3	Product 4
NSJ-Q	QB	Y	N	N
NSJ-R	Y	QB	Y	N
NSJ-S	N	QB	N	N
NSJ-T	N	Y	QB	Y

Figure 10. NSJ Cross Qualification Matrix

For each of four products for the chosen technology this table indicates if the NSJ is qualified to run the product (Y), is a qualified backup (QB) or is not yet qualified (N). Although this matrix seems a complex description of multiple products flowing through multiple pieces of equipment there are many toolsets at IFO that have much more complexity. This tool set was chosen for its relative simplicity as compared to several others at IFO.

Another important factor to understand when working with the NSJ equipment is that there is a strict rule for what is known at Intel as 'lot to lens'. Lot to lens rules dictate that a wafer must return to the same piece of equipment for subsequent processing as the one that performed the first process step. So, if on its first processing step at the NSJ a wafer was processed by NSJ-S then all three remaining layers must also be processed at NSJ-S. The main reason for this is variability reduction and traceability of defects. Lot to lens adds complexity to the manufacturing system as it causes further difficulty with line balancing.

After the wafer is processed each time by the NSJ (for a total of four times) it goes back into the manufacturing process for varying amounts of time. It was decided for the purpose of this model to treat the time between NSJ layers as one standard time for each layer. This means that there is a time for between layers one and two, another for between layers two and three, and yet another for the processing time between layers three and four. After layer four the wafer would be considered processed and would be complete for the purpose of the simulation. Finally, a standard changeover time of three minutes was used to represent a change in either product or layer at the equipment.

The following, Figure 11, is a screen shot of the Simul8 model used for the process flow of the wafers through the NSJ equipment. It shows the four products being entered to each of the four machines with the correct cross qualification. Also included are the intermediary process steps that take place between each layer. In addition, a rework loop was added that assumes to Model of Record (MOR) rework amount. This model was used for the baseline MOR comparison. It shows the perfect case scenario that the MOR is planned for. All timings and product volumes are dictated by MOR rates and are accounted for in this model as the MOR prescribes

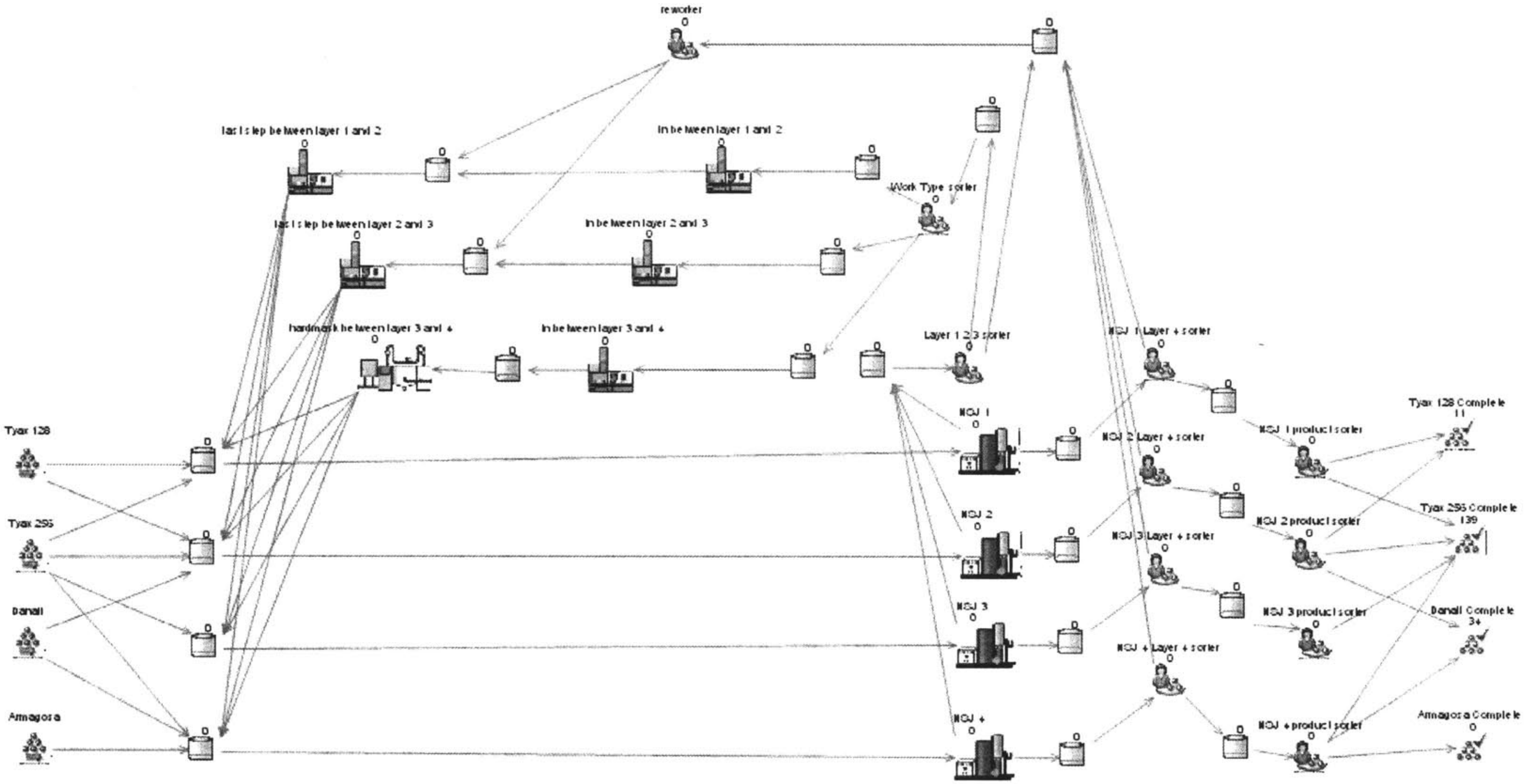


Figure 11. Baseline MOR Model Process Flow

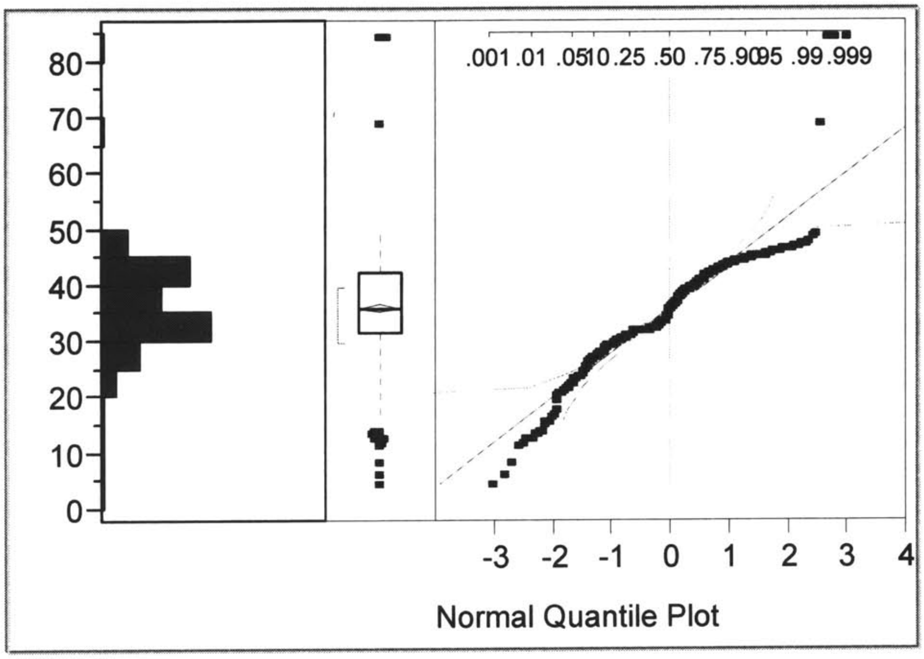
5.2.2 Creating the Actual Model and Determining the Machine Timings

Next, a second model was created to represent what has actually been happening at the NSJ equipment at IFO with the high mix, low volumes, and demand variances they have been experiencing. This model was created using the baseline MOR model and expanding it slightly to enable it to encompass what was actually happening. The major difference from the MOR model to the actual model is the machine timings. Instead of using the best case scenario MOR times for the equipment processing times, actual data was collected from over ten months of processing information. This data was then used to create unique distributions for each product at each machine layer.

When creating the distributions for NSJ run times one of the MOR buffer assumptions proved to be false. Since the MOR assumes that rework will occur only in full lot sizes it does not allow for lot sizes of smaller than 25 wafers being processed. In actuality, there are many wafers that are processed in lot sizes smaller than 25 wafers, and in fact, several that are processed in lot sizes of less than ten wafers. Because of this fact a single distribution was not feasible to represent actual processing times for wafers at the NSJ. Initially the model intent was to process each individual wafer in the actual model. However, the software proved incapable of processing this large amount of information and the decision to continue to represent the wafers as lots was made.

To solve the problem of having standard sized lots that process nearer to MOR timings and smaller rework lots that take much longer to process, two distinct product types were created for each product type within the model. This means that there are now eight types of 'products' flowing through the four NSJ machines. The first four are the standard wafer lots that have more than ten wafers per lot. The remaining four represent the smaller than ten wafer lots that are occurring in reality. Splitting the products into two groups allowed for the use of Gaussian (normal) distributions for each group and an easy processing flow for the model. More information about how the sensitivity of the model was tested and verified is included in section 5.3.2 below. Distributions were also created for the intermediary steps using over ten months of actual processing data. Again, Gaussian distributions were created based on actual machine timings between each NSJ processing step. To reduce complexity of the model standard rework amounts from MOR information and a standard changeover time of three minutes was used. Representative examples of two data sets are shown below in Figure 12 to verify their consistency with Gaussian distributed data.

Product 1 Layer 1



Product 2 Layer 1

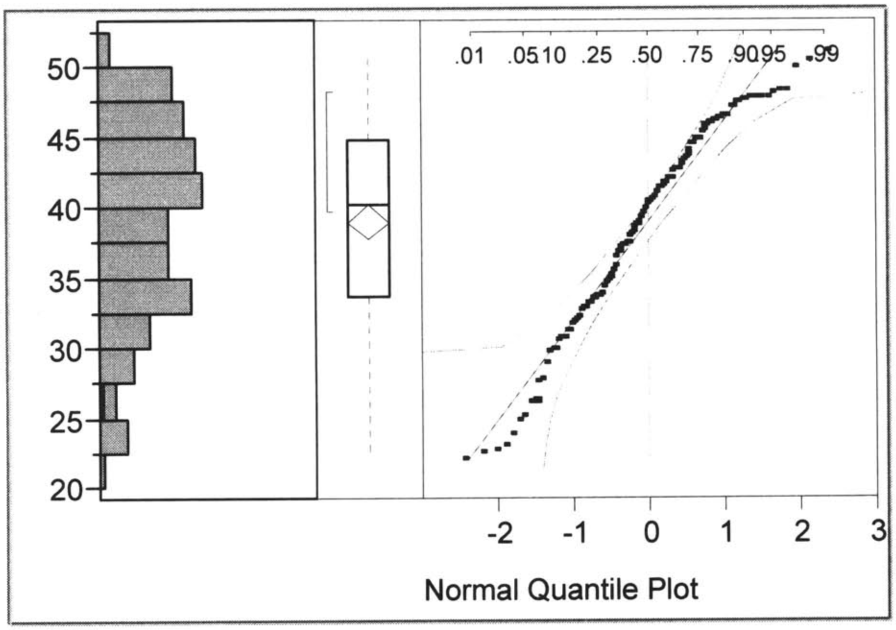


Figure 12. Gaussian Distribution Plots

Figure 13 below shows a screen shot of the Actual Model for four NSJ's processing four product types at IFO. As in the MOR model, this model adheres to lot to lens processing and accounts for intermediary process steps between each layer.

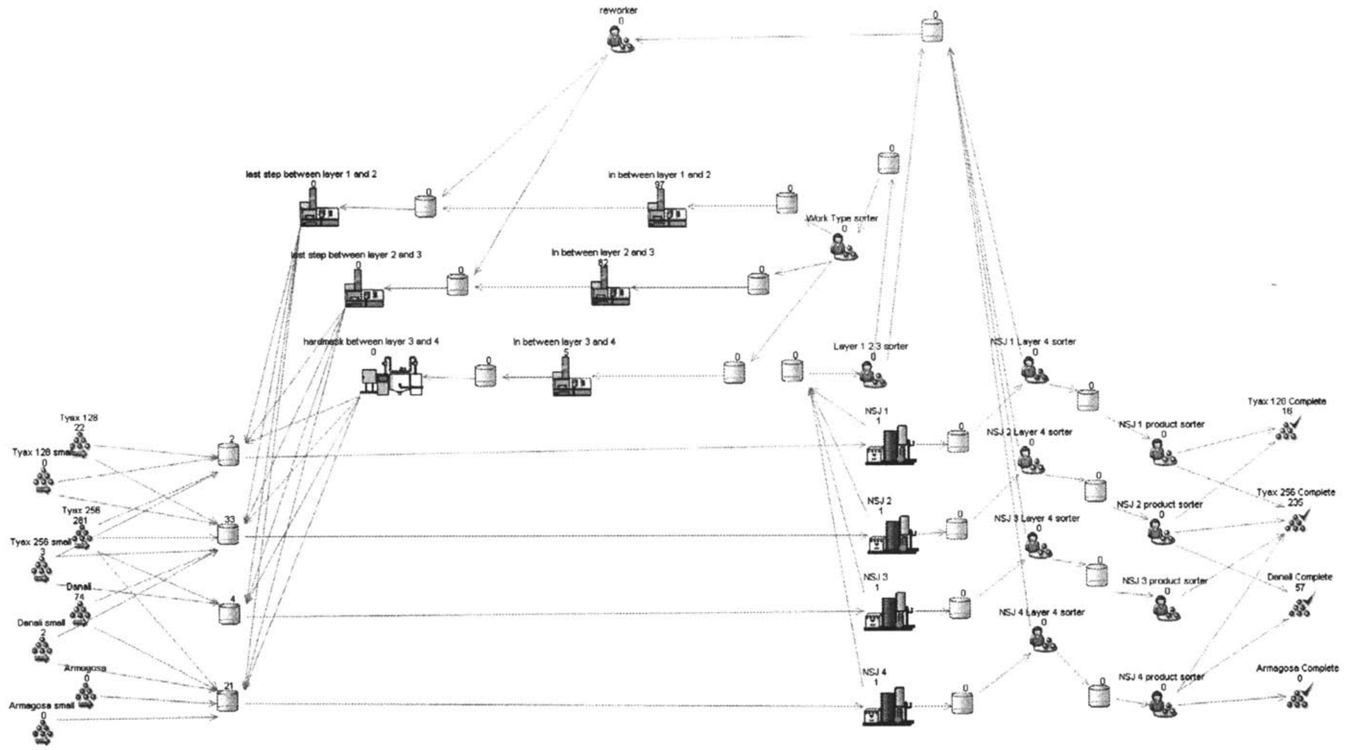


Figure 13 Actual Model Process Flow

5.3 Model Results

Once the models were created and processing times and distributions determined they were run several times and analyzed for different types of information. This section will describe how the models were run and will provide the results obtained from the models.

5.3.1 Verifying the Initial MOR Model

The first step in testing the validity of this experiment was verifying the MOR model results matched expected MOR processing times and amounts. In order to confirm that the model matched what the MOR was dictating, the model was run for a period of 24 weeks including eight weeks of simulation model 'warm-up' time to get the system filled to normal running conditions and 16 weeks of results collection time. The MOR expected amounts of processed material over the 16 week processing time period was achieved by the model for over thirty runs. These results were taken as verification that the MOR Simul8 discreet event simulation model was in fact modeling a fair representation of MOR predicted and dictated values.

5.3.2 Establishing Sensitivity of Actual Model and Software Limitations

Initially, as mentioned above, the actual model was set up to process each wafer as it's own entity—a step closer to modeling actual occurrences at the NSJ as compared to the multi wafer lots being processed by the MOR model. However, this level of detail made the model too complex and the software capability limit was reached. In order to obtain the needed results from the model, a switch back to lot processing was made. Section 5.2.2 above describes how the distributions were created for the two different lot size groups used for the actual model.

Although the software capability limit was reached there was still an attempt to obtain the best results possible. In order to do so, several scenarios were tested and are discussed in section 5.3.3 below.

5.3.3 Comparison of Model Outputs

This section will discuss the results obtained from the Simul8 discreet event simulation models. An attempt is made to compare the best case scenario MOR situation to what has actually been happening at IFO. Further, the erosion of buffers is made clear by presenting the difference in throughput times as well as waiting times in the system. Figure 14 below shows the difference in the amount of material processed by the system when MOR timings vs. Actual timings are used. For instance, for product one in the MOR model, 2,100 wafers were processed and in the actual model only 1,600 wafers were processed.

Product	MOR	Actual	% Actual less than MOR	% Actual is of MOR
1	2,100	1,600	24%	76%
2	27,700	23,500	15%	85%
3	7,000	5,700	19%	81%
4	0	0	N/A	N/A

Figure 14. System Throughput Comparison With Same Time Period Allowed

By examining the amount of material, or number of wafers, that each system is able to process in the same amount of time it becomes clear that the Actual model is lagging the MOR for all product types that are processed. The amount the system is able to process ranges from 76% to 85% depending on product volume and cross qualification of tools.

Another major difference between the wafers processed by the two models can be seen by examining the time each wafer spends in each system. Figure 15 below shows the average time in model time units each wafer spent in the two different systems.

Product	MOR	Actual	% increase in Actual time
1	1390	1826	31%
2	1392	1679	21%
3	1392	1560	12%
4	0	0	N/A

Figure 15. Average Time in System Comparison

For all product types that ran during the testing period the time in the system was greater in the Actual model. The increase in time spent in the system ranges from 12 to 31% of the MOR model timings.

These two evaluations and comparisons show that there is a clear difference between the two scenarios: Actual and MOR predicted. The important thing to focus on next is where are these differences coming from, i.e. what is causing them and can they be measured.

The most obvious place to look for differences between throughput times between the two models is the wait time the wafers spend in the system. This is the time they are idle, not being processed, but counted as WIP. Figure 16 below shows the increase in the number of wafers that have non-zero wait times for the NSJ machines experienced by the material processed in each system.

	Percentage of Wafers With Non-Zero Wait Times
MOR	54%
Actual	74%

Figure 16. Comparison of Wafers With Non-Zero Wait Times

Figure 16 above shows the percentage of wafers that experienced wait time at the NSJ equipment in each system. A 20% increase in wafers waiting to be processed has a huge effect on the efficiency of a manufacturing system. These wait times can be attributed to the increase in processing times for smaller lots as well as the increase in set ups and changeovers. The impact of these time drains on the system is much greater when each piece of equipment is considered a separate entity. However, for the simplicity of this model and to focus on the NSJ equipment, the collective wait time experienced at other points throughout the system are accounted for in the machine timings that represent the time each wafer lot spends being processed by all other steps in the model (represented as one process step as indicated above in section 5.2.1).

5.4 Conclusions Drawn From Experiment

This section will attempt to provide analysis and possible causes for the differences between the outputs of the two models. The main differences in throughput amount, time in system, and wafer lot wait time demonstrate the deterioration of the manufacturing process when several products at low volumes are produced. The increase in cross qualification of tools coupled with the small lots being processed leads to increased set ups and change overs as well as a decrease in process efficiency.

One of the major areas for increased time in the actual model concerns cascade efficiency. At the NSJ, as well as for other semiconductor processing equipment, many processes rely on wafer cascading to meet process times. The NSJ is set up to exploit a cascade efficiency by allowing the machine's track to fill with wafers of a similar type and lot causing the processing time for the second wafer to be shorter than the first. This efficiency is realized by all wafers after the first wafer and is realized by each wafer until the equipment track is full. Because the experiment conducted for this research paper dealt with wafer lots, not individual wafers, the cascade efficiency was factored into the timings that were used. The impact of smaller lots is a reduced cascade efficiency which is demonstrated by the slower processing times and reduction in system output.

Overall, this experiment shows the importance of updating capacity planning methods when a process is adapted to HMLV manufacturing. The differences between the results of the two models clearly show that HMLV manufacturing has a major impact on system efficiency and processing times. Further, the erosion of system buffers, such as cascade efficiency, rework lot size, and lower than four lot batch size can be expected to degrade the system enough to have serious impact—sometimes to the point where operating metrics can no longer be met. In some instances this may be so great that HMLV fabs may not be able to compete with HVM fabs unless more capacity is granted.

This page intentionally left blank

Chapter 6: Organizational Barriers

Mathematically determining a difference between two systems, one with MOR dictated timings and one using actual timings, is easy compared to taking these facts and creating action to implement changes based on the findings. This chapter will discuss some of the organizational challenges that exist for IFO as the organization transitions to a HMLV environment. An attempt is made to relate these issues to capacity planning as well as in general terms for IFO. The framework for this analysis is the "three lens analysis" described by Ancona, Kochan, Scully, Van Maanen, and Westney's article entitled "Managing the Future: Organizational Behavior and Processes". This article is used as a framework for analyzing organizations by all Sloan first year students and provides a general structure that can be compared across industry and geographic region.

It is important to note that this chapter is based on views that are entirely my own, ones developed from my experience working at IFO during an eight month period in 2004 and 2005. As this analysis is based upon observations made by one person during a relatively short time period, they are to be noted as such and considered in that light.

6.1 The Three Lens Framework

As mentioned above, the three lens framework for analyzing organizations is used by first year Sloan students to study organizations, and as the name suggests, utilizes three perspectives to explore the impact organizational change has on different groups. The following three sections will present each of the three lenses, discuss the viewpoint of the author regarding the relative position of IFO concerning each lens, and will present distinct challenges presented by IFOs current transition to HMLV as it relates to each lens. It is important to note that the three lenses overlap in many ways and are certainly intimately interconnected. Because of this a summary section is included to tie together the issues relating to organizational change experienced by IFO.

6.1.1 Strategic Design Lens

The strategic design lens examines how tasks and information flow through an organization. It deals with the way people "achieve goals by carrying out tasks" (Carroll, 2002). The strategic lens is the one that determines how organizational design effects the ways that people get things done in an organization, essentially the rules of the game that employees understand are necessary to abide by in order to get their projects completed.

In order to control these activities in a company managers create work groups, links between these groups, goals for the groups to work towards and achieve, and rewards aligned to the groups' success. How well these things are understood by all employees at all levels often can have a major impact on the success of the organization as a whole. This section will discuss IFO through the strategic design lens and provide some insights into how this has effected their transition to HMLV manufacturing.

One of the famous ways that Intel controls its process technology is by their "Copy Exactly" or CE! methodology. In general CE! has enabled Intel to rapidly fan out process improvements from their development sites. Basically the methodology is to create a stable process at a development fab and then transfer to a manufacturing facility while copying each and every item exactly to reduce variability and reduce the time it takes to get the production facility to produce quality product. This CE! methodology has worked well for Intel in the past and is one of the most important operating philosophies their employees follow. As IFO is transitioning to HMLV manufacturing CE! is causing some issues. Because IFO is required to copy all of the methods of high volume manufacturing sites, allowances are not made for their

HMLV environment. A good example of this is the Model of Record, or the tool used to plan capacity at Intel. As IFO transitions to HMLV manufacturing they have little to no control over changing the MOR to adapt to the changes. This essentially means that all of the buffers built into and assumptions made to the capacity planning system for high volume manufacturing are assumed to hold true for HMLV. As this thesis has demonstrated in Chapter 5, that is not always the case. Employees at IFO are currently struggling to find a balance between complying with CE! and developing HMLV 'friendly' metrics that are better suited to their new and unique environment. Two MIT LFM projects have now focused on aiding this transition and work continues by members of the permanent staff to try to find ways to overcome this hurdle.

Not only are processes being copied exactly from high volume sites to HMLV at IFO, but more importantly, so are measurement metrics. The strategic design lens deals with how people react to what they are measured against and developing a reward system for employees that meet the goals set out by their managers and the organization. When the equipment at IFO is being used to run several products at low volume (and therefore the employees responsible for maintaining, running, and monitoring that equipment) are held to the same standard as equipment running high volumes of standard products, metrics are difficult to meet. When throughput is measured, changeovers lead to machine downtime and metrics can be missed. This fact is currently causing an issue at IFO as many tool sets are unable to routinely meet their goal amounts for utilization or availability. This is leading to a situation for employees that is frustrating and difficult to change within the CE! environment.

Currently IFO workgroups are organized by equipment areas of the fab. These groups are responsible for specific process stages and equipment tool sets within the factory. Members of each group are linked to the other equipment groups within IFO as well as within Intel's Virtual Factory or "VF". The VF is the grouping of Intel employees across sites that are running similar technologies.

The VF's main purpose is control over changes and knowledge share. Its intent is to avoid repetition and maintain process control throughout the various worldwide sites. At IFO, only higher level managers have significant involvement with the VF and entry level engineers' involvement does not seem to be an attractive job responsibility. Upper management sees linking with the VF to be an extremely important aspect of manufacturing strategy at Intel but many employees, especially at lower levels, do not recognize this.

Mentioned above are a few of the struggles experienced by IFO in their transition to HMLV manufacturing that are caused by Intel's strategic design. Although their strategy works for many cases and shouldn't be changed for IFO alone, there are some factors that could be amended or adapted to different manufacturing environments. Many employees at IFO insist that although they are part of Intel they still do things 'an Irish way' which can be taken as notice that not all things can be applied the same way in all cultures. Similarly, Intel cannot expect to CE! their entire strategy when the manufacturing environment changes. The recommendation section will provide some suggestions for IFO to incorporate some of their realities into the Intel strategic design.

6.1.2 Political Design Lens

The political design lens analyzes the power struggle among different employees with varying underlying interests (Carroll, 2002). It examines how people form groups and coalitions to make sure their individual objectives are met. The political design lens is concerned with how negotiations are handled within the organization and which people hold the power to create change and give and hold information within the organization. This section will discuss how the politics of working at IFO has affected their transition to HMLV manufacturing.

In order to understand the difficulties transitioning to HMLV manufacturing imposes on IFO, this section will focus specifically on the project scope discussed in this thesis. Narrowing the focus will enable us to see concrete examples of politics in action at IFO, something that is often more difficult to discuss in a broad sense.

When considering the different departments and workgroups affected by investigating if the Model of Record (MOR) capacity planning tool can be adapted to better apply to a HMLV environment, the following stakeholder analysis map was created:

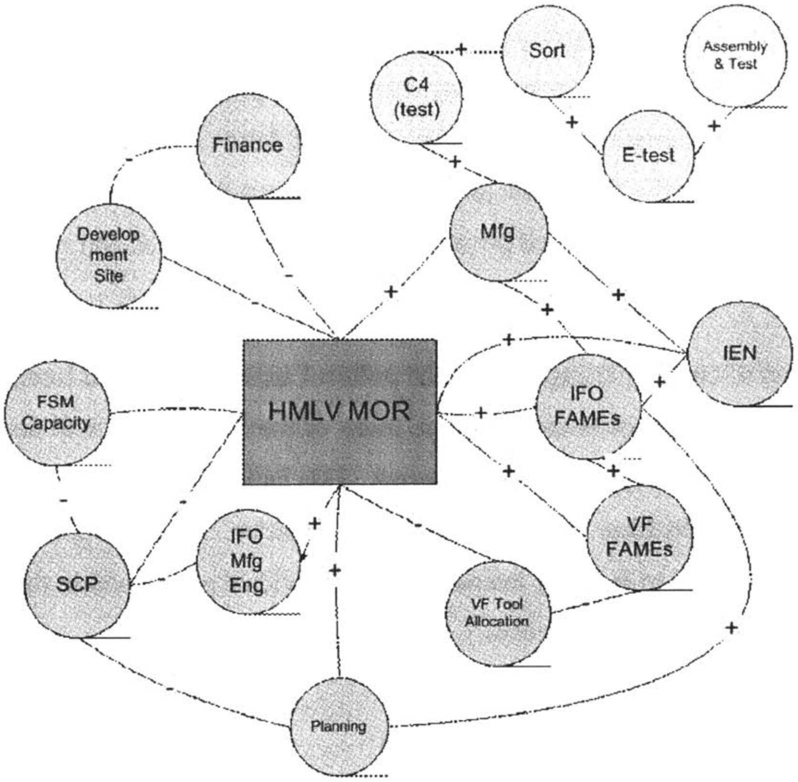


Figure 17. HMLV Friendly Stakeholder Analysis Map

Each of the different work groups are represented as well as their interaction with the project and with each other. The '+' and '-' signs on the diagram represent if the department or group viewed the project as favorable (+), or unfavorable (-). Conducting this analysis brings to light the political motivations of group members and enables us to see where support and opposition may be derived.

Because this project was extremely self contained within the IFO Manufacturing Engineering group, support was generally very high. Opposition does exist from other support functions; however this was not experienced directly while the project was being conducted. In reality, pressure will be seen in the implementation stage as HMLV manufacturing drives further changes to methodologies formerly governed by the CE! mentality discussed in the previous section.

Within the IFO manufacturing engineering group where the project was conducted the political support for the project was strong. Because the project was seen as not having a direct impact on employee's day to day activities, but as having a potential to create improvements in the future, the project did not pose a threat to current operating practices. Further, employee project involvement was limited and required no more than a few hours of involvement each week.

In the broad aspect of creating change within the political aspect of IFO and Intel, transitioning to HMLV will not be easy. In fact, many of the changes that will need to be made pose a threat to current operating norms. This includes things from employee interaction to decision making, and metric evaluation. From the political perspective, IFO will need to increase interaction and individual power within the VF in order to realize some of the necessary changes.

6.1.3 Cultural Design Lens

The cultural design lens examines how people use informal relationships to determine how work in an organization is accomplished. It considers the history that is involved in creating meanings that are assigned to situations within an organization (Carroll, 2002). The cultural design lens is the most pervasive and the least tangible of the three lenses, facts that make it the hardest to analyze and change.

In general, Intel has a culture that values technological achievements. This makes sense because it is important to their success as a company to be the technical leader in their field. An example of this is their efforts to meet Moore's Law. Some suggest (even Moore himself) that perhaps Moore's Law has been met because of the statement of it by Gordon Moore. Whether this is true or not, technology dominance is a key strategic goal of the company that has permeated its culture. Intel has a policy of 'constructive confrontation' that enables employees to operate in a technology focused environment. Basically, they stress setting the record straight quickly and efficiently and questioning others sooner rather than later. They believe that having this policy removes many of the obstacles traditionally associated with one employee questioning another in the workplace. For many Intel employees constructive confrontation works well, for others, it is accepted.

As mentioned earlier, many at IFO believe that although they follow 'Intel's rules', they still do it with an 'Irish perspective'. This can mean many things to different people or when examined in different perspectives. This section will discuss what the author has interpreted this to mean for the manufacturing engineering group at IFO.

There is not a lot of constructive confrontation occurring in IFO's manufacturing engineering group. Instead, there is a general sense of camaraderie that exists amongst the employees that allows them to communicate openly with each other and respect each other. This work group is extremely cohesive on many fronts. For example, people are authentic and readily help each other when help is needed. Learning is valued and all members of the group are respected for their unique perspective. People that work in this group genuinely seem to enjoy each other's company and work well together to reach common goals.

Based on limited observations of other work groups within Intel, the IFO manufacturing engineering group seems to be an anomaly. This stems from the individual personalities in the group, the Irish culture in general, and the group leadership. All of the members of the workgroup participate in daily ergonomic stretching sessions designed to prevent injuries. However, this time is also used for people to interact with one another and therefore reinforces the culture of the group.

As IFO further transitions to HMLV the strong culture of their workgroup will be an asset they can leverage to manage change. Because their employees are dedicated to helping one another and there are many positive and supporting aspects to their culture, they need to recognize these formally and integrate them into the change process.

6.2 Recommendations

Several organization barriers exist that may hinder IFO's future success in transitioning to a HMLV wafer fab. However, recognizing these barriers and creating a plan to overcome them will alleviate many problems for IFO. This section will provide recommendations for IFO to consider as they continue their transition to HMLV. It should be noted that these recommendations are made by an individual that spent a relatively short time (eight months) at IFO as compared to the time it takes to develop a company or workgroup culture, or communicate and implement a company strategy. As such, these recommendations are intended to facilitate minor changes along their journey.

In order to enable members of IFO to be leaders in their transition to a HMLV manufacturing site, an increased involvement in the VF is needed by all levels of employees. IFO needs to align incentives for VF interaction and its employees should become power leaders within the VF. In the vain of the squeaky wheel getting the oil, IFO needs to continually make their HMLV challenges heard. They also need to become the leader with respect to HMLV manufacturing and be the company authority on future implementation aspects.

Creating power for IFO within the VF will enable them to drive change in regards to how they are measured and which metrics may need to be adapted to fit an HMLV environment. IFO employees are in the best position to see which aspects of CE! translate to HMLV and which ones do not. They need to take the lead in communicating this to the VF and develop solutions to overcome the obstacles CE! causes when it does not translate for them.

The strong culture within the IFO manufacturing engineering group should enable them to easily drive these changes from within the group. They should leverage this strength and use it to create change and build support for the resolution of their issues within the VF.

This page intentionally left blank

Chapter 7: Recommendations for Intel and Conclusions

This thesis has attempted to show the impact that transitioning to an HMLV manufacturing environment can have on capacity planning. Chapters one through four provided background information about Intel, the sponsor company of this project, manufacturing basics, high mix low volume manufacturing, and capacity planning methodologies. Chapter five discussed the formulation and results of two discreet event simulation models that represent a specific toolset within Intel's IFO operation. The purpose of this chapter was to demonstrate the gap that exists between current capacity planning methods and what actually happens in an HMLV operating environment. Chapter six discussed the organizational barriers that currently exist that may present obstacles to the continued success of HMLV transition at IFO as well as providing suggestions for overcoming some of these barriers. Finally, this chapter provides a brief summary of the study findings as well as concluding with recommendations for future actions to be taken by Intel to ease their transition to HMLV and how these tools may be applicable in several industries and environments.

7.1 Summary of Conclusions and Recommendations

The discreet event simulation experiments conducted as part of this thesis clearly demonstrate the gap between MOR predicted values and what is actually occurring at IFO. Without a large scale recognition of this fact and the following adaptation of metrics tailored for HMLV environments IFO will continue to struggle to meet the demands the high volume manufacturing metrics are demanding. Further, consistent failure to meet or exceed demands with current capacity planning methods will eventually erode morale at IFO and could lead to a culture that does not value metrics they do not see applying to their situation. This circumstance could occur if IFO employees are forced to deal with capacity planning methods created for high volume sites that no longer apply in their environment, especially as they gather concrete evidence of the gap that exists between their situation and the situation being copied from.

In order to avoid the diminishment of the importance of metrics at IFO actions need to be taken to create metrics that are adapted to their facility and environment. Employees at IFO need to take the lead in creating these metrics. One way they could achieve this is by gaining a stronger presence and power within the Virtual Factory (VF) and subsequently using this power to bring attention to their situation. In order for this to be most effective, IFO employees also need to be providing suggestions and solutions to the VF for alleviating the issues and creating positive situations for IFO and Intel.

IFO should be able to leverage their strong culture of team work and respect to further their cause within the VF. Also, the results of this study provide them with concrete evidence to support their claim that should be extremely useful within Intel's technology focused culture. Having numbers applied to the situation will bring them credibility and should act as a foundation for their future claims.

7.2 Recommendations for future work at Intel

IFO is continuously shifting further towards higher mix with lower volumes. As this transition progresses issues that seem minor will grow. To avoid crisis situations later on, IFO employees need to continue to tackle projects aimed at smoothing the transition to HMLV. This can be accomplished through continuing to focus the efforts of the OpX team on HMLV issues. These changes will require the continued support of upper management as well as the involvement of front line employees at IFO. The importance of soliciting and rewarding the involvement of lower level employees in this effort cannot be overlooked. In fact, currently these employees are not having their capabilities fully utilized as evidenced by their lack of representation in the VF. Including all levels of employees is a lesson from Japanese lean principles that also applies to IFOs current situation.

7.3 Applicability of Findings to Other Industries and Companies

This thesis focused on the effect of transitioning a semiconductor wafer fab from high volume manufacturing to a HMLV environment to equipment capacity planning. Although there was a narrow focus, the findings can be applied to other companies and industries. For example, the results of the simulation study show that an increase in product mix has a significant effect on equipment utilization and processing amounts. This will hold true for any product or industry—if mix is increased that calls for increased set up times and changeovers, slower throughput times can be assured. Also, the importance of adapting metrics throughout the transition process applies to other industries. Employees often focus on what they are measured against and correct metrics will drive the desired behaviors. The findings of this thesis show that changing operating environments without changing metrics can cause problems in any industry. Measuring employees in different environments with the same metrics can, in extreme situations, lead to distrust and confusion that should be avoided.

This page intentionally left blank

References

Ancona, Kochan, Scully, Van Maanen, and Westney. Managing the Future: Organizational Behavior and Processes. 2nd Edition. South-Western College Publishing. Boston, MA. 1999.

Carroll, John. "Introduction to Organizational Analysis: The Three Lenses". MIT Sloan School. 2002.

Goldratt, E.M., The Goal. Great Barrington, MA: The North River Press, 1992.

Hopp, W. J. and Spearman, M. L., Factory Physics: Foundations of Manufacturing Management. McGraw-Hill, 1996.

Intel website. www.intel.com. 2005

Kelly, Brian. Intel Internal PowerPoint Presentation. "Kelly_HMLV Presentation R3". 2003.

Killian, Vida, "Impact of High-Mix Low-Volume Products in Semiconductor Manufacturing". LFM MIT Thesis, 2003.

Mahoney, Michael R. High-Mix, Low-Volume Manufacturing, Prentice Hall PTC. Upper Saddle River, New Jersey, 1997.

Miltenburg, John, Manufacturing Strategy: How to Formulate and Implement a Winning Plan, Productivity Press. Portland, Oregon, 1995.

Newlin, Anthony, "Equipment Protective Capacity Optimization using Discreet Event Simulation". LFM MIT Thesis, 2000.

Pandolfo, Chris, " Optimization of In-line Semiconductor Measurement Rates: Balancing Cost and Risk in a High Mix, Low Volume Environment. LFM MIT Thesis 2004.

Porter, Michael E. Competitive Advantage: Creating and Sustaining Superior Performance, The Free Press. New York, 1985.

Public Broadcasting System website. www.pbs.org. 2005