Lean Manufacturing System Design and Value Stream Management in a High-Mix, Low-Volume Environment

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Abstract

Value Stream Mapping is a powerful tool for identifying sources of waste and for creating the vision for the future state of a production system. As a management tool, however, it lacks in specific focus of roles, responsibilities, and actions required to achieve the future state vision. The limitations become more evident and the problems of execution become exacerbated when multiple value stream projects are launched with limited human resources available. This thesis describes a set of management tools to complement Value Stream Mapping. The tools are expected to improve management visibility and accountability.

The design of a lean production system is also proposed in this thesis. The lean production system includes a newly designed layout for the manufacturing cell as well as the “operating system” for the cell. The layout is based on the principles of cellular manufacturing in order to promote flow and improve quality. The operating system includes such things as production batch sizes, product routings, and strategic inventory locations. Based on the future state value stream map and supported by a discrete-event simulation, the new operating system is designed to align the lean strategy with the technical capabilities of the manufacturing line. As confirmed by the simulation, implementation of the new production system is expected to reduce lead time for the cell by 2/3, realize a corresponding one-time reduction in inventory of $350,000, and increase on-time delivery of the cell to over 97%. In total, the project has a three-year net present value exceeding a quarter of a million dollars.

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I dedicate this thesis to my family and to Sarah.
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Chapter 1: Introduction

“Welcome to Windsor Locks Mechanical Operations.” So reads the sign welcoming visitors to Hamilton Sundstrand’s manufacturing facility in north-central Connecticut. This facility, the world-headquarters for Hamilton Sundstrand (a division of United Technologies Corporation), is in the middle of an “Operations Transformation.” Operations Transformation is a four-pronged strategy to increase operating income margin and inventory turns in each of United Technologies’ factories.¹

Lean manufacturing and Value Stream Mapping comprise one of the strategic foci of Operations Transformation. Amidst the largest downturn in aviation history, the aerospace industry is facing flat-to-negative pricing pressure forcing manufacturers and suppliers to reduce costs, reduce inventories and reduce lead times, becoming ever more efficient in their production and supply chain operations. George David, Chairman and CEO of United Technologies, proclaims that lean manufacturing methods “have been the single greatest force behind our economy since the early 1990’s.”² Indeed, implementing lean and implementing it correctly are vital to Hamilton Sundstrand’s continued success in the aerospace industry.

1.1 Background and Discussion of the Problem

The mechanical operations manufacturing facility in Windsor Locks produces (among other products) air conditioning systems for military and commercial aircraft. These systems are assembled from hundreds of in-house manufactured and purchased...
parts or sub-assemblies. In order to reduce cost, reduce lead time, and increase responsiveness to changing customer demand, a transformation to lean manufacturing methods was initiated at the upper-most assembly levels. In order to be completely successful, however, the lean transformation was carried down to the lower assembly levels including all in-house manufactured parts. This research focuses on two aspects of a lean transformation: the management of value stream projects, and the design of a mixed-model lean flow line that supplies the upper-level assemblies and spare part customers with high-speed rotational parts called “rotors”.

Value Stream Mapping (VSM) is a powerful tool for establishing the future vision of a production system. As a management tool, however, it lacks in specific focus of roles, responsibilities, and actions required to achieve the future state vision. The limitations become more evident and the problems of execution become exacerbated when multiple value stream projects are launched with limited human resources available. A set of management tools are developed, therefore, to set the strategic value stream priorities, establish goals, track performance, and stabilize the changes. This results in improved management visibility and improved execution of value stream projects.

The second aspect of this research examines the design of a lean manufacturing system. The rotor manufacturing area currently uses a batch and queue system to produce dozens of different part numbers for different aircraft air conditioning systems. The batch sizes typically range from 12 – 20 parts, and machine cycle times can range from a few minutes to many hours depending on the part type and the operation. As a result, the area is presently characterized by long lead time, poor on-time delivery, and
high inventory even through product cost and quality are excellent. The challenge, therefore, is to transform the manufacturing area into a lean flow line such that lead time is reduced and on-time delivery is improved. The major constraint in this effort is an inability to further reduce setup on a long-setup operation at the beginning of the line. Without a solution to this problem, batch sizes could not be reduced from their present values as set by the economic lot quantity (ELQ) equation, the new line would not operate in a lean fashion, and little improvement to the metrics would be realized.

The lean effort commences with a value stream map of the process. This step is fundamental to understanding the impact of batch and queue production to the manufacturing system. The future state map also sets the stage for understanding a potential solution to the batch size and setup time problem. The solution is to utilize a strategic supermarket of inventory to decouple the long-setup upstream process from the downstream processes, and to use different batch sizes in the two parts of the line. We present a discrete-event simulation based on the future state to confirm the approach and also understand and evaluate other tradeoffs in the operation of the new system. The simulation is crucial to understanding the effects of various choices in product routing, in essence evaluating the capacity of the perceived bottleneck with a high degree of precision.

We present a layout of the new manufacturing line in parallel with the analytical design effort. The layout needs to balance the desires of numerous stakeholders, from management, to the operators, to the lean practitioners including the author. This aspect of the research is certainly the most frustrating, as there are an infinite number of possible arrangements for the equipment, and choosing a layout is much more art than science.
Implementation of the redesigned system did not occur during the author's internship. Hamilton Sundstrand is, however, beginning to implement the batch size segmentation strategy at present. It is not clear when the new layout will be implemented. The anticipated benefits of fully implementing the lean manufacturing system in the rotor cell include a reduction in production lead time by \(\frac{2}{3}\) with a corresponding reduction in WIP inventory amounting to $350,000; on-time delivery increased from a baseline of 60% to over 97%; and a corresponding ability to build and deliver the higher-level air conditioning systems on time. Overall, the net present value of the project exceeds a quarter of a million dollars over a 3-year timeframe.

1.2 Key Ideas and Hypotheses

Many production systems are a product of history. Systems developed around the principles of mass production may have worked in the past when cost, variety and lead-time were less of an issue. Many manufacturers have begun a transition to lean manufacturing methods to cope with recent changes in the competitive landscape, in order to reduce costs, improve quality and improve responsiveness to changing customer demand.

Often, the lean efforts have focused on isolated process improvements. While these are necessary, they are not sufficient. Instead, the entire value chain needs to be examined as a coordinated system. Value Stream Mapping, recently popularized with the publication of a how-to guide, is a good tool for discovering waste throughout the value chain and creating a vision of the future production system. Yet it is not an obvious tool for managing the improvements. One hypothesis of this work is that a set of management
tools can be created to define, prioritize, execute and sustain the projects identified through value stream mapping.

The slow evolution of many production systems also leads to misalignments within the system. Process improvements designed to create a leaner production process still operate under the existing assumptions of mass production. Systems, such as HR and accounting, that are there to support the production process, suddenly control the production process. New equipment, designed to improve efficiency and reduce cost, has unintended consequences on lead time and inventory. In short, elements of the production system over time become misaligned with the organization’s strategy. The second major hypothesis of this thesis, therefore, is that lean transformation needs to look at the whole. A complete system redesign helps align the manufacturer’s production capabilities with its lean strategy. Indeed, the achievements of 2/3 lead time reduction and increasing on-time delivery to greater than 97% would not be possible with individual process kaizen.

1.3 Organization of the Thesis

This chapter provides a short background to the current operations transformation efforts at Hamilton Sundstrand and a short introduction to the thesis projects. In addition, the chapter presents the motivations for the projects and key hypotheses developed from the research.

Chapter 2 presents a brief introduction to United Technologies and Hamilton Sundstrand. The origins of lean efforts within the division as well as within the larger Corporation are reviewed. Finally, the chapter presents a brief literature review for lean manufacturing and value stream mapping.
Chapter 3 discusses the background for value stream mapping at United Technologies and within the Mechanical Operations organization at Hamilton Sundstrand. The chapter presents the objectives of value stream mapping, but also the difficulties typically encountered when implementing value stream projects. A set of tools to manage value stream projects is presented that is expected to improve execution and sustainability of the projects.

Chapter 4 presents the lean system design efforts for the rotor cell. The motivation for the project is reviewed, along with an extensive analysis of the current manufacturing system. The objectives of a lean production system are reviewed and contrasted to the current state. Value stream mapping is used as the first step in the redesign effort to discover sources of waste in the current system and create a vision for the future system. The redesign effort commences along two fronts: redesigning the physical layout of the cell, and redesigning the systems elements, including things like batch sizes, product routings, and strategic uses of inventory. A major focus is to obtain alignment between production capabilities and the lean strategy throughout the new rotor cell. A discrete-event simulation is presented that analyzes the system.

Chapter 5 presents the results and conclusions of the rotor cell redesign project. The analysis concludes that vast improvements can indeed be realized through substantial changes in the production system. A net present value calculation shows a positive return exceeding a quarter of a million dollars over a three-year timeframe. The chapter concludes with a discussion on the importance of systems-level redesign.

Appendix A presents a detailed discussion of the simulation developed to analyze the new production system.
The thesis is written at a level that assumes the reader is familiar with lean manufacturing and value stream mapping. Where appropriate, detail will be provided so that the reader can understand the results and conclusions presented, but the thesis is not intended to teach details such as the symbols used in value stream mapping. The workbook Learning to See\(^3\) is an excellent reference for learning value stream mapping. Nevertheless, Appendix B provides a brief refresher to the meaning of the symbols used in value stream mapping.

\(^3\) Mike Rother and John Shook, Learning to See, (Brookline, MA: Lean Enterprise Institute, 1998).
Chapter 2: Background, Historical Review, and Literature Review

This chapter presents a brief introduction to United Technologies and Hamilton Sundstrand, and also provides a brief history of lean manufacturing at Hamilton Sundstrand. The beginnings of lean at Hamilton Sundstrand can be traced to the 1980's, yet it was not until the beginning of this millennium that a comprehensive lean program was fully institutionalized at all of the Hamilton Sundstrand sites, including Windsor Locks. The chapter concludes with a literature review of lean texts and previous LFM theses on lean manufacturing.

2.1 Background of United Technologies and Hamilton Sundstrand

United Technologies Corporation (NYSE: UTX) is an industrial diversified company headquartered in Hartford, CT with 2003 revenues of $31 billion. Employing just over 205,000 people world-wide, the company consists of eight independent business units: Carrier heating and air conditioning, Chubb security and fire protection services, Hamilton Sundstrand aerospace and industrial systems, Otis elevators and escalators, Pratt & Whitney aircraft engines, Sikorsky helicopters, UTC power (fuel cells), and United Technologies Research Center. UTC has been named Fortune Magazines “Most Admired Aerospace Company” for the past four years in a row.

With 29 major manufacturing, distribution and repair facilities around the world, Hamilton Sundstrand is one of the largest global suppliers of aerospace and industrial products. The aerospace division designs, manufactures and services aerospace systems. These systems include electrical power generation and distribution systems, flight control systems, fuel systems, environmental control systems, propellers, gearboxes, and
electronic controls and components. Hamilton Sundstrand’s aerospace systems can be found on over 90% of the world’s aircraft. On the industrial side of the business, major products include mechanical power transmissions, pumps, rotary screw air and gas compressors, pneumatic tools, and marine drives.

Hamilton Sundstrand was formed in 1999 with the merger of Hamilton Standard with the Sundstrand Corporation. Hamilton Standard, which is the legacy division within United Technologies Corporation, traces its roots to 1919 and the Standard Steel Propeller Company. The Sundstrand Corporation can trace its roots to 1905 and the Rockford Tool Company.

The impressive list of innovations at the two legacy companies includes the first controllable-pitch propeller, the constant-speed drive for generating uniform AC electrical current off a variable mechanical input, one of the first hydromechanical fuel control systems, the world’s first electronic engine control system, and the world’s first electronically controlled cabin pressure regulating system.

2.2 Brief Historical Review of Lean Manufacturing at Hamilton Sundstrand

Both legacy Hamilton Standard and the Sundstrand Corporation can trace their beginnings in lean manufacturing to the 1980’s. At Hamilton Standard, the beginnings of lean manufacturing can be found in setup reduction efforts in the Windsor Locks facility during the mid 1980’s. While these efforts and other kaizen improvement efforts were sustained into the 1990’s and beyond, other efforts in creating pull systems and focus factories around this time were not continued beyond the latter half of the 1990’s.

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The ACE program, created by United Technologies in the early 1990’s, while not exactly lean manufacturing per-se, was the first widely-adopted effort towards quality improvement at Hamilton Standard. ACE, or Achieving Competitive Excellence, is grounded in principles of six-sigma and continuous improvement. The ACE toolkit includes the elements of 5s, total productive maintenance, root cause analysis, mistake proofing, standard work, setup reduction, and others. These elements have had tremendous success at improving manufacturing quality and reducing cost. They have been instrumental to helping Hamilton Sundstrand achieve the process reliability, quality, and level of safety required of a lean production system. But ACE does not implicitly include lean elements such as specifying and identifying value, creating flow, and using pull instead of push.

The true beginnings of lean at Hamilton Sundstrand can be found in the heritage Sundstrand Corporation. There, in the mid-1990’s, the company began to create part families and use kaizen events to reduce cycle time and improve reliability in order to move towards a just in time (JIT) philosophy within manufacturing cells. In 1997, the efforts were formalized and given the name “Market Rate of Demand (MRD)”. The program was carried over into the newly-formed Hamilton Sundstrand when the legacy Sundstrand Corporation was acquired by United Technologies in 1999. MRD has since evolved into a philosophy and set of techniques through which customer satisfaction is improved by on-time delivery, competitive cost, and exceptional quality. MRD strives

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5 Ibid, 17.
for single piece flow of work, controlled by kanban, with point of use material and
tooling in production cells.\textsuperscript{6}

Most recently, United Technologies kicked off a new initiative called Operations Transformation. Broader than any of the previous philosophies, operations transformation expands to include strategic sourcing, low-cost sourcing, and design for manufacturability in order to increase operating margins. In addition, value stream mapping was specified along with lean manufacturing as a key element of operations transformation. Chapter 3 explores operations transformation in more detail.

United Technologies and the legacy Sundstrand Corporation both provided elements of what today is considered lean manufacturing at Hamilton Sundstrand. A complete and complementary set of tools through the ACE, VSM, and MRD programs give Hamilton Sundstrand the fundamentals for implementing lean manufacturing.

2.3 Literature Review

This thesis focuses on two efforts: the management of value stream mapping projects, and the design of a lean manufacturing system for a low-volume mixed-model production line. Literature in both of these areas is reviewed.

The Toyota Motor Corporation is widely recognized for creating the revolution in manufacturing that is today known as lean manufacturing. While some of the elements of lean, such as a focus on identifying waste, creating flow, pull of material, and just in time, can be traced to the early 1900's, it was Toyota that first put all of these elements together. Along with innovations created by Toyota, these principles became institutionalized at Toyota and are known as the Toyota Production System (TPS).

\textsuperscript{6} Ibid.
At Toyota, TPS practitioners work to establish flow, eliminate waste and add value. In the process, TPS practitioners use a mapping technique they call “Material and Information Flow Mapping” to depict the current flow of material, information and people, and also to create a map of the ideal future state.  

While many of the tools of TPS have been documented, including kanban systems, kaizen events, and cellular manufacturing, the tool for creating material and information flow maps until recently had not been documented. In 1998, in an effort to help manufacturers focus on flow instead of isolated process improvements, the Lean Enterprise Institute (LEI) published the book Learning to See by Mike Rother and John Shook. This was the first text dedicated to Value Stream Mapping (VSM). Since its publication, other LEI texts by the same authors have been written to extend the tool to the enterprise level. In addition, other texts have since been written that include explanations of VSM.

Learning to See is a fairly comprehensive step-by-step guide for creating a current and future state map. It includes a chapter on achieving the future state; that is, using the tool to actually implement changes. As will be discussed in Chapter 3, however, the tools presented are incomplete. Apparently the LEI recognizes this, as they currently offer three $750 seminars dedicated to Value Stream Management. The newest, “Policy Deployment – Bridging the Ingenuity Gap,” is described as a workshop to “guide you in "de-selecting" initiatives down to the ones the organization can really achieve while aligning them with company strategic objectives.” Another workshop, “Managing with Maps” provides a “comprehensive system for managing implementation activities along

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7 Mike Rother and John Shook, Learning to See, (Brookline, MA: Lean Enterprise Institute, 1998), Introduction by Mike Rother and John Shook.
multiple value streams.” And finally, the seminar “Leadership for Value Stream Management,” explains how, “As firms have changed their focal planes, they have found that they are usually ill-equipped to actually manage according to their new-found vision.” Clearly, there is a need (and a market) for tools to manage value stream projects.

Now, these tools need not be unique to value stream mapping. General project management tools are perfectly applicable, and project management is a well-documented field. In fact, a search on Amazon.com of the term “Project management” returns 69,078 titles. Therefore, there is no need to review the literature in the field of project management.

The second aspect of this research focuses on creating a lean production system. There are several texts that are considered ground-breaking in their discussion of lean. The first, The Machine That Changed the World, was published in 1991 and authored by James Womack, Daniel Jones and Daniel Roos. The authors spent five years studying Toyota and other auto manufacturers as part of the International Motor Vehicle Program at MIT to discover the differences between Toyota’s production strategy and mass production practiced in the west. It was in this book that the term “lean production” was coined.9

Based on the success of the first book, two of the authors, Womack and Jones, went on to publish Lean Thinking in 1996. The intent of Lean Thinking was to

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8 LEI seminar titles and descriptions found at http://www.lean.org/Events/#value
summarize and teach the principles of lean production and also to present in case study form the successes of early lean adopters in the United States.

Another author, JT. Black of Auburn University, wrote the text *The Design of the Factory With a Future* that was published in 1991. While the term “lean” is not used by Black (since it was not yet coined), he nonetheless presents an excellent methodology for creating an “integrated manufacturing production system,” in other words a Toyota Production System. Black details 10-steps to a redesigned factory. Some of the steps include the creation of cellular manufacturing and assembly cells, setup reduction, pull production control, the integration of quality control, production control and inventory control into the cell, and extending the concept to the supply base. This text was very useful to the author’s research.

There are dozens of previous LFM theses that involve lean production at various partner companies. Even though lean production in the US is now over ten years old, it continues to be a popular subject for LFM internships; in the class of 2004, at least 11 internships focused on lean manufacturing and/or value stream mapping. Some of the recent LFM lean theses are discussed next.

Jonathan Rheaume’s 2003 thesis was titled, “High-Mix, Low-Volume Lean Manufacturing Implementation and Lot Size Optimization at an Aerospace OEM.” Rheaume’s work was conducted at Hamilton Sundstrand and provided an optimization technique for inventory lot sizing and a method to coordinate production runs in order to reduce the frequency of setups on long setup equipment.\(^{10}\)

Ankur Goel studied the materials development and manufacture of organic light emitting diodes at Kodak. His 2003 thesis, “Chemicals Development and Lot Size Optimization for Low-Volume, High Value OLED Chemicals” focused on aligning research and product development teams that interface with manufacturing. He studied lot sizing decisions in an environment where very-low-volume materials present a challenge for an inventory-averse organization. He also developed a mixed-integer linear program to optimize batch sizes for the mix of chemicals expected. Make/buy decisions were studied for the chemicals. Finally, he used critical chain project analysis to discover a key bottleneck in material testing that hampered development.11

Vida Killian studied the impact of high-mix low-volume production at Intel Corporation. Her 2003 thesis, “The Impact of High-Mix, Low-Volume Products in Semiconductor Manufacturing” finds that the integrated circuit cards for the telecommunications industry are different in mix and volume from the traditional semiconductor products Intel produces. For a company that is accustomed to high-volume low-mix production, Killian addresses the high-level question of how Intel’s manufacturing system will be impacted by the addition of high-mix low-volume products. She develops a framework to analyze the change in manufacturing strategy.12

There are literally dozens of additional LFM theses on the subject of lean manufacturing, but in the spirit of adding value, these three examples will suffice.

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Chapter 2 presented an introduction to United Technologies and Hamilton Sundstrand. The foundations of lean manufacturing at Hamilton Sundstrand evolved over the 1980’s and 1990’s at both the legacy Hamilton Standard Corporation and the Sundstrand Corporation, in addition to the larger United Technologies Corporation. The combination of ACE, VSM, and MRD elements developed by the three, constitute an effective lean manufacturing program. The chapter concluded with a literature review of value stream mapping and lean manufacturing. Both fields are well-covered in the literature, through papers, books, and LFM theses. The next chapter will present a more-detailed discussion of value stream mapping, including tools developed to help execute VSM projects.
Chapter 3: Operations Transformation and Value Stream Mapping

"The propensities of large and mature organizations are toward mediocrity, resistance to change, and risk avoidance. The tasks of management are to avoid these traps."  
George David

This chapter begins with a description of an initiative at United Technologies called “Operations Transformation.” It continues with a discussion on an important piece of Operations Transformation, called Value Stream Mapping (VSM), and how VSM integrates with previous approaches to lean at Hamilton Sundstrand. The chapter then discusses the need for management tools to plan and execute value stream projects and presents such tools.

3.1 Objectives of Operations Transformation

The Operations Transformation initiative was launched at United Technologies Corporation during a company-wide conference on January 16-17, 2003. The conference was attended by the top operations personnel from each business unit. Presenters included George David, Chairman and CEO of United Technologies, Steve Page, the vice-Chairman and COO, and various presidents and vice-presidents from the different business units (Pratt & Whitney, Hamilton Sundstrand, UTC Power, Carrier, Otis, and Sikorsky).

The challenge presented to the attendees was to use the elements of Operations Transformation to grow operating income margin by 6% and double inventory turns by 2006. The elements of Operations Transformation include lean manufacturing with

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13 George David, Chairman and CEO of United Technologies Corporation, in remarks during the Operations Transformation Conference, East Hartford, CT, January 16-17, 2003 (taken from video).
value stream mapping, design for manufacturability, strategic sourcing, low cost
sourcing, and talent and leadership.\textsuperscript{14}

While all five elements are necessary for success, this research focuses on the lean
manufacturing with value stream mapping element and the tools needed to successfully
use value stream mapping.

3.2 Value Stream Mapping

Value Stream Mapping (VSM) is a key component of Operations Transformation 
and UTC’s objectives to grow operating income margin and inventory turns. Identifying
the value stream is also considered by Womack and Jones to be the second lean principle
following the identification of value from the customer’s perspective.\textsuperscript{15} The purpose of 
value stream mapping is to sort every action required to design, order, or make a specific
product into three categories: (1) those which actually create value as perceived by the
customer; (2) those which create no value but are currently required by the system and
can not be eliminated yet; and (3) those actions which do not create value as perceived by
the customer and can be eliminated.\textsuperscript{16}

Even though value stream mapping was described by James Womack and Daniel
Jones in their book \textit{Lean Thinking} in 1996, many organizations, in their haste to
eliminate waste through kaizen activities, skipped this critical step.\textsuperscript{17} Womack and Jones
found that in doing so, many companies were able to fix small parts of their value

\textsuperscript{14} Operations Transformation video with excerpts from Operations Transformation Conference, held
January 16-17, 2003, East Hartford, CT, produced by United Technologies Corporation.
\textsuperscript{16} Ibid, 37-38.
\textsuperscript{17} Mike Rother and John Shook, \textit{Learning to See}. (Brookline, MA: Lean Enterprise Institute, 1998),
foreword by Jim Womack and Dan Jones.
streams, but overall realized little net improvements to the bottom line.\textsuperscript{18} It wasn’t until 1998, with the publication of \textit{Learning to See} by Mike Rother and John Shook, that step-by-step instructions for value stream mapping became available to a wide audience.

Rother and Shook’s toolkit approach to VSM helps companies apply lean techniques strategically within the context of a lean value stream. This helps companies think to create flow instead of creating isolated process improvements.\textsuperscript{19} Indeed, even though many isolated improvements through the use of lean manufacturing techniques were previously generated at Hamilton Sundstrand, the absence of the value stream mapping tool made the importance of flow understated.

\textbf{3.3 Link Between VSM and MRD}

Jonathan Rheaume’s 2003 internship at Hamilton Sundstrand and subsequent thesis detailed Hamilton Sundstrand’s “Market Rate of Demand” program, or MRD. The MRD program, combined with the UTC-wide quality initiative called “ACE,” can together be considered synonymous with lean manufacturing at Hamilton Sundstrand. Rheaume’s thesis, “High-Mix, Low-Volume Lean Manufacturing Implementation and Lot Size Optimization at an Aerospace OEM,” describes the objective of MRD and the steps in implementing an MRD project. The objective of MRD is to standardize and to simplify processes while simultaneously improving quality and responsiveness to customer demand. Ultimately, MRD strives to improve cycle time, productivity, inventory, quality, customer on-time delivery, and safety.\textsuperscript{20}

\textsuperscript{18} Ibid.
\textsuperscript{19} Ibid, Introduction by Mike Rother and John Shook.
The steps to implement an MRD project are:

1. Kick-off of cross functional team / overview training
2. Initial Data Collection
   - 80/20 Volume Breakdown
   - Bill of Material Analysis
   - Demand Pattern
   - Baseline Metrics
3. Process Analysis
   - Process Flow Maps
   - RBWA’s (Routing By Walk Around)
   - Part/Process matrix
   - Design, Quality, Supplier, Material issues
   - OEE (Overall Equipment Effectiveness)
4. To-Be Process Definition
   - Part Families
   - Standard Processes
   - MRP Cell
5. Resource Requirement Calculations
6. Kanban Design Analysis
7. Define Cell Layout / Simulation
   - MRD Cells
   - MRP Cell
8. Final Presentation
9. Equipment Procurement / Transition Plan
10. Implementation

As can be seen by the steps, VSM was not traditionally a part of lean transformation at Hamilton Sundstrand. Indeed, value stream mapping was only initiated at Hamilton Sundstrand as a result of the Operations Transformation conference in January, 2003. Today, VSM is considered the first step in an MRD project. VSM can also be performed on a stand-alone basis for process improvement without a full MRD implementation. This was the path chosen for the lean system design of the rotor manufacturing cell described in Chapter 4.

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21 Ibid, 19.
3.4 Management of Value Stream Projects

The VSM activity – mapping the current process, identifying those steps which do not create value, and developing the future state process through which waste is reduced – can be very powerful for aligning the focus to system-wide improvements. Given the ease and power of VSM to highlight waste, a quick flurry of VSM activities commenced in May, 2003 at Hamilton Sundstrand. An “Operations Transformation Conference Room” was quickly covered with end-to-end current state and future state value stream maps for multiple products. Even with the step-by-step guide contained in “Learning to See,” however, Hamilton Sundstrand experienced difficulties executing the transformation from current state to future state.

3.4.1 Need for Project Management Tools

The future state map portrays a compelling vision for reducing waste and improving business productivity. Yet it does not contain any information on how to make the changes, who is responsible for making the changes, or when those changes should be made. In addition, there is often “information overload” as the future state could contain dozens or hundreds of “kaizen bursts,” the action-oriented process improvements that may be required to support the future state, and the symbols and terminology used may be unfamiliar to everyone but the lean experts. The future state also often cuts across existing organizational boundaries, further complicating roles and responsibilities. A comprehensive set of management tools is therefore needed to help execute and sustain the changes to achieve the future state. In other words, a management system is needed.
3.4.2 Review of Existing VSM Management Tools

Learning to See attempts to address these issues with a chapter on achieving the future state. The chapter presents two tools: (1) a high-level yearly value stream plan that schedules critical activities necessary to achieve the future state, and (2) a value stream review to evaluate progress against the goals.22

The yearly value stream plan, shown recreated in Figure 1, has a number of limitations. First, a yearly plan is at too high a level to contain the details necessary for executing a complex transformation to lean. A weekly or daily schedule showing all the activities necessary to execute the kaizen activities and support the transformation is preferable since a detailed schedule will help manage the potentially large number of individual kaizen events. The yearly plan is a good tool, on the other hand, for scheduling the high-level strategic plans of a factory. For example, in months 1-3 execute the future state plan for the rotor line, in months 4-6 execute the future state plan for the nozzle line, in months 7-9 execute the future state plan in the valve line, etc. This is particularly useful if the human resources that will be used are the same across the projects. This helps upper management set the priorities for the top projects and helps balance workload with resources.

The second tool presented in Learning to See is a value stream review, shown recreated in Figure 2. This tool evaluates the progress of each implementation objective and is intended to be reviewed between the value stream manager and a higher manager. As designed, this tool is a useful way to audit progress against goals. It could be

22 Mike Rother and John Shook, Learning to See, (Brookline, MA: Lean Enterprise Institute, 1998), 90-95.
improved, however, by making the evaluation less subjective and by instituting policies through which the review frequency is adjusted.

While the two tools presented in Learning to See have certain strengths, there is a conspicuous absence of other tools which could compliment this set to further help execute and sustain the changes that are part of a lean transformation. The next subsection details the complete toolset created for value stream projects at Hamilton Sundstrand.
## Figure 1: Yearly Value Stream Plan

<table>
<thead>
<tr>
<th>Product Family Business Objective</th>
<th>V.S. Loop</th>
<th>Value Stream Objective</th>
<th>Goal (measurable)</th>
<th>MONTHLY SCHEDULE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Person in charge</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Jan</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Signatures

<table>
<thead>
<tr>
<th>PLAN MANAGER</th>
<th>UNION</th>
<th>ENGR</th>
<th>MAINT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Reviewer</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## Figure 2: Value Stream Review

<table>
<thead>
<tr>
<th>Plant-Level Objective</th>
<th>V.S. Loop</th>
<th>Objective &amp; Measurable Goal</th>
<th>Progress Conditions</th>
<th>Evaluation</th>
<th>Remaining Problems</th>
<th>Points and Ideas for Coming Year’s Objectives</th>
</tr>
</thead>
</table>

○ = Success  △ = Limited Success  × = Unsuccessful

Product Family:
3.4.3 Overview of VSM Management System

The VSM management tools create a system by which teams and management can choose the important value streams to focus improvement, identify the key improvements within those streams, schedule the work, and track and review progress. The absence of this type of system is what prevented Hamilton Sundstrand from fully realizing the benefits of Value Stream Mapping. This is because all too often, daily production issues and “fire fights” would take priority over the longer-term value stream improvements. The VSM management system attempts to create an agreement and framework between the value stream teams and management that the improvements are of the same importance as daily activities. It does this through a set of tools. These tools, adapted largely from a University of Michigan short-course\textsuperscript{23}, are presented.

The VSM management system includes a set of tools by which:

- Opportunities are identified, quantified and prioritized,
- Teams are chartered, supported by management and lean experts, with clear responsibilities and boundaries,
- Detailed work plans are created,
- Metrics are tracked,
- Progress is reviewed,
- And the system is stabilized.

A symbolic representation of the process is presented in Figure 3. The sub-sections that follow the figure present details on each of the process steps.

\textsuperscript{23} "Managing Value Stream Improvement," University of Michigan Center for Professional Development
Figure 3: Value Stream Mapping Management Process

1. Management selects strategic value streams for focus

2. Create Current State Map

3. Create Future State Map

4. Identify, Quantify & Prioritize Opportunities (Goal Document)

5. Team Chartered to implement target opportunities

6. Create work plans
   Track key metrics

7. Implementation & project reviews at least bi-weekly

8. Audit and stabilize system changes

9. Closure
   > Celebrate success
   > Release resources

LEGEND:
- Management
- Team with Mgmt Support
- Team
3.4.3.1 Strategic Value Stream Selection

This step is performed by the senior management team. The purpose is to strategically select the project(s) that should be performed first, considering such things as perceived value, resources, and fit within any larger strategic plans. For example, at Hamilton Sundstrand, the senior factory leadership team decided to move the rotor manufacturing area and subsequently change it into a lean flow line (the subject of Chapter 4) in order to free the square footage for another product. They also recognized that reducing lead time and improving on-time delivery of the rotors would help improve on-time delivery and reduce build cycle time for the air cycle machines and air conditioning systems that the rotors feed into.

3.4.3.2 Current State Map

Once a strategic value stream has been selected, a team is formed and chartered to map the current state. This team should consist of personnel (management and hourly) from the area being mapped, along with any support personnel (such as manufacturing engineering, design engineering, facilities, customers, or lean coordinators) that may be desired.

The objective of the current state map is to walk the process from customer to supplier in order to identify all process steps, process step metrics (cycle time, process time, changeover time, number of people required, number of shifts, reliability and yield), inventory, and information flow. This sets the stage for creating the future state map – the next step. A picture of an actual current state map is shown in Figure 4.
Frequently, the current state value stream map will reveal the inefficiencies of the existing production process. These inefficiencies are sometimes a result of unreliable machines, long setup times, and the use of batch and queue production processes, typically leading to large amounts of inventory between each process step and long production lead times. The "lead time ladder" at the bottom of the value stream map attempts to quantify the amount of processing time required at each step (on the lower steps of the ladder) and the amount of lead time ahead of each process step based on the inventory ahead of each process step (the upper steps of the ladder). By summing across the lower steps and upper steps, the team can get an indication of the ratio of total production lead time to total process lead time. Often, this ratio is very low, indicating a high amount of non-value added activity in the system. For more information on the details of value stream mapping, the reader is referred to Learning to See.
Figure 4: Current State Value Stream Map

Figure 5: Future State Value Stream Map
3.4.3.3 Future State Map

The future state map shows the first evolution of waste removal. It will ideally represent a chain of production where the individual processes are linked to their customer(s) either by continuous flow or pull, and each process gets as close as possible to producing only what its customer(s) needs when they need it.²⁴ A picture of an actual future state map is shown in Figure 5.

The future state map should be created by the same team that created the current state map, and it should be done within a day of creating the current state map so that the participants do not forget what they learned while walking the current state.

Recall from Figure 3 that the value stream improvement process should be a never-ending cycle. Therefore, the team developing the future state map should try to achieve the ideal state described above, but should not assume miracles will happen to get there. For instance, the first generation of a future state map will often assume that the existing product design, and existing machinery and technology cannot be changed. The team will therefore look for sources of waste not caused by these items. After the first phase of waste-removal is achieved, the team can go back and create a new current state and future state map in the spirit of continuous improvement, perhaps challenging some of the original assumptions.

The future state will likely contain numerous “kaizen bursts,” or process improvements, supporting the transition to flow or pull. Some of these bursts may be perceived as simple, while others may be complex. Some may involve only one organization, while others may cut across many organizational boundaries. In addition,

²⁴ Mike Rother and John Shook, Learning to See, (Brookline, MA: Lean Enterprise Institute, 1998), 57.
the future state will likely contain alternate strategies for product delivery and flow, including supermarkets, FIFO lanes, and kanban signals. Successfully implementing these changes is what the remaining tools were designed to help accomplish.

3.4.3.4 Goal Document and Kaizen Prioritization

There are two tools used to quantify and prioritize the opportunities resulting from the future state. The first tool is the goal document, a sample of which is shown in Figure 6. The goal document establishes high-level goals or targets for improvement in the future state. For example, the overall lead time in the future state may be compared to the current state to establish a goal of 33% lead time reduction. Likewise, a goal may be 50% inventory reduction. The purpose, of course, is to establish targets by which the success of the project can be evaluated.

The second tool is a more detailed prioritization of kaizen bursts. This activity takes a weighted average of each team member's inputs to establish the importance, or priority, of executing the kaizen improvements. The criteria are typically ease of implementation, speed of implementation, reduction in inventory and cycle time, increase to customer satisfaction, increase to safety, and cost/benefit ratio. These criteria, of course, could be changed depending on the project or the team's objectives.

A prioritization sheet, shown in Figure 7, is given to each team member. The criteria are listed across the top and each is given a different weighting on a scale of 1 to 10 depending on its perceived importance. Each individual kaizen activity is listed down the rows. Each team member then fills out the spreadsheet rating each kaizen activity on a scale of 1 to 5 against each criterion, with a score of 5 being the best. All team members' inputs are then averaged within each criterion, and summed across the criteria.
to rank the kaizen activities. Figure 8 shows the ranked kaizen activities with a clear explanation of how the scores were achieved.

The goal sheet and kaizen prioritization are admittedly subjective. The purpose of the future state map, recall, is to progressively identify waste to be removed. Within the future state there will likely be numerous improvements to execute. The high-level goal document and the detailed-level kaizen prioritization worksheet provide a quick but subjective method for the team to identify the high-leverage projects. From this list of projects, team can be chartered to execute the projects. This is the next step.
<table>
<thead>
<tr>
<th>Item</th>
<th>Current State</th>
<th>Future State</th>
<th>% Change (Expected)</th>
<th>% Change (Actual)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Total Production Lead Time</td>
<td>28 d</td>
<td>19 d</td>
<td>-33 %</td>
<td></td>
</tr>
<tr>
<td>2. Inventory</td>
<td>$20 k</td>
<td>$10 k</td>
<td>-50 %</td>
<td></td>
</tr>
<tr>
<td>3. Total process time</td>
<td>310 min</td>
<td>280 min</td>
<td>-10 %</td>
<td></td>
</tr>
</tbody>
</table>

Note: values are examples only and are not representative of actual cell metrics

Hamilton Sundstrand
A United Technologies Company
**Figure 7: Sample Kaizen Prioritization Matrix**

<table>
<thead>
<tr>
<th></th>
<th>Level of Difficulty</th>
<th>Implementation Time</th>
<th>Inventory/Cycle Time</th>
<th>Customer Satisfaction</th>
<th>Safety</th>
<th>Cost/Benefit</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pack Assembly</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eliminate inspection</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Create FIFO lanes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Improve yield at assembly</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Schedule trucks (pitch run) shipping - automatic schedule</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Improve method of moving 777 fixtures</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eliminate extra 777 fixtures</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moving assembly line</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eliminate pack leak inspection or sampling</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fix o-ring damage @ pack assembly</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eliminate excess inventory PX details - set-up pull with suppliers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>POU storage of components with visual signals of pulls</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ACM Assembly</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eliminate leak test/Move to ACM area, else in advance of leak test</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Improve turn time of receiving bin stock from 2A</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Understand and fix ACM test if required/Dry air</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quality clinic approach to test failures</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supermarket for ACM Assembly</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combine balance, performance, leak, and electrical bonding tests</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cross training (Assembly and test)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FIFO - ACM Final inspect</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Housings</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FIFO with trigger from supermarket at matched housings</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Define EPEI every machine</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material handling improvement to eliminate damage</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reduce multiple handling steps in receiving</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eliminate unpackage &amp; waste disposal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transportation receiving to work station</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 8: Using the Prioritization Matrices to Determine Weighted Average Priorities

Each team member fills in matrix, individually evaluating each activity on scale of 1 to 5 under each criterion.

Team determines criteria and criteria weighting (on scale of 1 to 10) before distributing evaluation sheets to team members.

A score of 5 is always the “best” condition. For example, lowest level of difficulty, shortest implementation time, greatest reduction to inventory or cycle time, etc.

Simple weighted average i.e. score = \( \frac{(3+1)}{2} * 6 = 18.0 \)

Total across each row. Higher score indicates higher relative importance to implement.

### Weighted Average Results

<table>
<thead>
<tr>
<th>Activity Description</th>
<th>Team Member 1 Weighted Score</th>
<th>Team Member 2 Weighted Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eliminate inspection</td>
<td>24.0</td>
<td>28.0</td>
</tr>
<tr>
<td>Create FIFO lanes</td>
<td>24.0</td>
<td>28.0</td>
</tr>
<tr>
<td>Improve yield at assembly</td>
<td>24.0</td>
<td>24.0</td>
</tr>
<tr>
<td>Schedule trucks + parts + shipping + automatic schedule</td>
<td>24.0</td>
<td>24.0</td>
</tr>
<tr>
<td>Eliminate extra 777 fixtures</td>
<td>16.0</td>
<td>16.0</td>
</tr>
<tr>
<td>Eliminate pack leak inspection or sampling</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Fix o-ring damage @ pack assembly</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Eliminate excess inventory PX details + set-up pull with suppliers</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>POU storage of components with visual signals of pulls</td>
<td>5.0</td>
<td>5.0</td>
</tr>
</tbody>
</table>

Team member 1:
- Weighted score calculations are shown for each activity.

Team member 2:
- Similar to Team member 1, with slight variations in scores due to individual evaluations.
3.4.3.5 Charter Team(s)

The goal sheet and kaizen prioritization help identify high-leverage projects that transform the current operation to the future state. These projects should be given formal charters that identify the team members, team champion (leader), lean coach, and sponsoring manager. The charters will also identify the deliverables, metrics, generic timeline, boundary conditions, and constraints. In other words, the charter provides the overall structure for each project. Note that depending on scope, the future state value stream and corresponding goals can spawn from 1 to perhaps a dozen individual charters. The individual charters are then managed as reasonably-sized independent projects. As such, there is much higher likelihood of the future state being achieved than if the whole future state transformation is given to an individual or team to achieve. As independent projects, it is not necessary (nor perhaps appropriate) that each charter have the same team members, leader, sponsor and coach. A sample charter is shown in Figure 9.

To be maximally effective, it is recommended that all chartered projects be of a scope and scale that they can be accomplished in 30 to 90 days. This length of time has been found to be an effective balance between allowing enough time for a significant project to be undertaken while not being so long that the team loses focus.

It is very important that the teams be chartered based on resource availability. That is, it is pointless to charter a half-dozen projects with the same team members when there is no reasonable expectation that the team members will have enough time to accomplish all the chartered projects. It is better to charter only the projects that have a reasonable expectation of being accomplished simultaneously. After completion of some
of these projects, additional project charters can be sequentially drafted to continue the improvement efforts.

The relationship between the team champion and sponsor is of utmost importance. The champion is the leader of the team and is personally invested in seeing the team succeed. The champion has the resources, energy, and desire to lead the project to completion. The sponsor is a manager-level leader who is underwriting the activity of the team. The sponsor is usually not a member of the chartered team, but provides support for the team to succeed, while also imposing accountability. Their relationship is key. The champion must get a clear message that the project is important to the sponsor, and that the champion is accountable for continued progress. The sponsor should spend time weekly with the champion to challenge thinking and thoroughness, and, with help from the coach, provide needed support.
Figure 9: Sample Team Charter

Value Stream Team Charter

Name of Team: Aluminum Rotor Flow Line

Objectives: Design, lay out, and implement a single-piece continuous flow line for aluminum rotors. Utilize kanban pull from ACM assembly.

Sponsor: Steve

Leader: Annie

Coach: Pete

Team Members: Adam, Joe, Pierre, Shaheen

Deliverables: Floor layout, implement line procedures / standard work, changes to processes, setup times, equipment (as necessary).

- Metrics: Total lead time, inventory, on-time delivery %
- Timeline: July through Mid-September 2003
- Reviews: Team reviews weekly with Sponsor


Sponsor: A manager level leader who is underwriting the activity of the team. The sponsor is usually not a member of the team, but provides support for the team to succeed, while also providing accountability. The Sponsor meets weekly with the team Leader to challenge thinking and thoroughness of the team and to provide needed support. The Sponsor is accountable to the Operations Leadership Team for the success of the team.

Leader: The Leader heads the team and is personally invested in seeing the team succeed. (S)he has the accountability to facilitate the process through to completion. (S)he is accountable to the Sponsor for continued progress and success.

Coach: The Coach provides educational and directional support to teams upon request of the Leader. The Coach coordinates Lean efforts throughout the site.
3.4.3.6 Work Plans and Metrics

Once a team is chartered and the key deliverables identified, the team should then plan the detailed activities necessary for accomplishing the improvement. This schedule is captured in a detailed work plan, a sample being shown in Figure 10. The detailed work plan is a simple Gantt chart that helps assign tasks to the team members, establishes timing, and tracks progress. Along with the work plan, tracking the key metrics helps the team and management see the effects of the improvement actions. A sample key metric tracking sheet is shown in Figure 11. The tracking can be done on a daily or weekly basis and provides a simple, direct measure of the improvements’ impacts.

3.4.3.7 Project Reviews

Progress reviews should be held at least bi-weekly between the project champion and the sponsor, and should only take 15-30 minutes per charter. The purpose is to check the progress of the actual implementation against the plan, and to review the status of the key metrics.

As simple as this may sound, this is perhaps the most important step of all to successfully accomplishing a value stream improvement project. Again, the relationship between the sponsor and project champion is key. Project reviews reinforce the importance of the project to the sponsor and champion. Without accountability on the champion, continued support by the sponsor, and investment by each party, the improvement activity will not be viewed as important and little progress will be made.
# Hamilton Sundstrand
**A United Technologies Company**

## WORK PLAN

### PROJECT: Aluminum Rotors

**Project Start Date:** 7/1/2003  
**Finish Date:** 9/15/2003

### WORK PLAN

**Page 1 of 1**

<table>
<thead>
<tr>
<th>No.</th>
<th>Action Item</th>
<th>Due Date</th>
<th>Person(s) Assigned</th>
<th>July</th>
<th>August</th>
<th>September</th>
<th>Review Meetings</th>
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<tr>
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<td>Cell design training</td>
<td>14-Jul</td>
<td>Team</td>
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<td>Adam</td>
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<td>Joe</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>Establish lot size through lathe &amp; mill</td>
<td>22-Aug</td>
<td>Pierre</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>Shaheen</td>
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<td>0</td>
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<td>Team</td>
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<td>13</td>
<td>Move Cell</td>
<td>3-Sep</td>
<td>Team</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>14</td>
<td>Link via Kanban</td>
<td>3-Sep</td>
<td>Adam</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>15</td>
<td>Mill QCPC data collection</td>
<td>15-Sep</td>
<td>Adam</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>16</td>
<td>Operators Fully Trained</td>
<td>15-Sep</td>
<td>Pierre</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>17</td>
<td>Adjust as necessary</td>
<td>15-Sep</td>
<td>Team</td>
<td>0</td>
<td>0</td>
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<td>Team</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

### Legend:
- **O** Proposed Start  
- **△** Proposed Completion  
- **◎** Actual Start  
- **△△** Actual Completion  
- **◎◎** Review Meetings  
- **O** Green - On Target  
- **O** Yellow - Behind Target  
- **△** Red - Immediate Attention
Figure 11: Sample Key Metric Tracking Sheet

Hamilton Sundstrand
A United Technologies Company

Key Indicator: Inventory

Program: Aluminum rotor cell

Month: September

Measure (units)

|          | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | Avg |
|----------|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| Initials |    |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | $22,000 |
| Last Mnth Avg |    |   |   |   |   |   |   |   |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | $16,000 |

Note: values are examples only and are not representative of actual cell metrics
3.4.3.8 Audit

The audit sheet provides a formal mechanism for ensuring improvement activities are not short-lived and become standard process. An audit checklist (sample shown in Figure 12) is used to evaluate items specific to each target area. A simple yes or no evaluation is used to generate a numeric score. Note that the questions should be written such that a “yes” is the desired condition. As the score improves, audit frequency can be reduced. The figure provides a suggested audit frequency in relation to audit score. Any items which receive a “no” should be commented on so that the team can develop a corrective action. Note that the audit checklists, key metrics and work plan should be displayed in the area so that all people in the area can see and understand the progress being made.

3.4.3.9 Celebrate Success and Release Resources

The final step to each chartered project is to capture all the key data and activities of the project, quantify the actual results, and celebrate success! At this point the team members and leader should be formally “released” from the project such that they are freed to potentially begin a new improvement project. The next project is, of course, chosen based on the value stream work plan and/or the strategic implementation plan.
## Figure 12: Sample Audit Sheet

![Audit Sheet](image)

<table>
<thead>
<tr>
<th>#</th>
<th>Question</th>
<th>Yes</th>
<th>No</th>
<th>If no, please comment (be specific)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Are all parts authorized by a Kanban?</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Are FIFO limits being observed?</td>
<td>X</td>
<td></td>
<td>Glass burr FIFO exceeded</td>
</tr>
<tr>
<td>3</td>
<td>Are all mini-cells being operated correctly?</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Is lathe operation being triggered by a signal Kanban?</td>
<td>X</td>
<td></td>
<td>Excess material in supermarket</td>
</tr>
<tr>
<td>5</td>
<td>Are all cells clean, organized and 5s'd?</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Are metrics updated on schedule?</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Do all parts flow forward only?</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Are resources being allocated appropriately?</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Have hot lists been obsoleted?</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Is Takt time being met?</td>
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</tr>
<tr>
<td>25</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

# Additional comments or concerns (if there is not enough room above):

- Audit weekly until a score of 90% or above is reached for 3 consecutive weeks
- Audit bi-weekly until a score of 90% or above is reached on 3 consecutive audits
- Audit monthly

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3.4.4 Summary of VSM Management

Value Stream Mapping is an extremely powerful tool for identifying waste in a value stream. It helps all participants see where improvements are needed and projects how much those improvements could be worth to the company in terms of lead time and inventory. Yet the tool gives little guidance on how to actually accomplish the improvements and sustain their effects.

A value stream management system was therefore developed to strategically identify the important value streams, map the current and future state, set and prioritize goals, formally charter teams, develop a schedule, track progress, and stabilize the system through the use of audits.

Initial indications of the tools’ success at Hamilton Sundstrand are positive. The tools have been used on a number of heat exchanger value stream projects. One of the successes of the tools’ use has been to help align management expectations with the reality of limited human resources. The charters and work plans provide a clear indication of when resources overlap or become over-committed. Another benefit of the tools is that the charters, work plans, and audits are posted along with the current and future state maps in the work areas. This gives all the people involved in the improvement process, including the operators, visibility into the overall objective and fosters better communication between management and the workforce.

Recently, Hamilton Sundstrand completed additional large-scale value stream events in the propeller manufacturing business at Windsor Locks. Three of the value stream maps created were repeats of maps that were created in 2003, but for which the future state was never acted upon or implemented. The reason that the future state was
not implemented was because there was no management system by which to identify and prioritize the improvement activities, assign roles and responsibilities, and track progress. This year, the attendees at the value stream mapping event saw a marked improvement from last year’s activities in that today Hamilton Sundstrand has a process by which to manage the transition to the future state. The attendees were assigned to teams with charters, given deliverables, a schedule, and responsibility to report on progress on a regular basis. The attendees remarked on how they were confident that the future state would be achieved this time now that Hamilton Sundstrand has and uses a method to manage the process.25

Chapter 4: Lean System Design

This chapter presents the design of a mixed-model lean production system for machined parts called “rotors”. The chapter begins with the motivation for the project and gives a brief explanation of the rotor manufacturing process. The chapter continues with an extensive exploration into the existing production system, including the existing layout of the manufacturing cell, the standard cost accounting system, the demand profile for the parts, and the equipment utilized. Understanding the complexities of the existing process is essential to developing and understanding a proposed solution.

A value steam map of the current and future state provides a roadmap for designing the new system. The new system includes a new layout for the manufacturing area and a production strategy including such things as the segmentation of parts into product families, lot size policies, routing of parts through machines, and strategic inventory locations. Chosen to promote product flow, these variables are analyzed using a discrete-event simulation. The simulation validates the design and shows that operational metrics such as on-time delivery and lead time will be dramatically improved in the new system. Although actual implementation was not initiated during the internship, the simulation predicts that upon implementation, on-time delivery will improve from approximately 60% in the existing state to over 97% in the proposed state. Likewise, lead time will be reduced from about 25 days in the existing state to about 6 days in the proposed state, with a corresponding reduction in WIP inventory.
4.1 Introduction

Rotors are high-speed rotational components that are part of aircraft air-conditioning systems. The air conditioning system consists of the following major components: heat exchanger, air cycle machine, and valves. Generally two or more different rotors are part of each air cycle machine, and each air cycle machine is designed uniquely to each aircraft model. Currently, there are about $73$ different rotor part-numbers in production, each part-number unique in its design. The manufacturing process for rotors will be discussed in the next section, but in general every rotor goes through the same high-level manufacturing process, though at a detailed level there is no "standard process" for manufacturing a rotor. The rotor cell epitomizes a high-mix low-volume environment. As will be explained in Section 4.6, the mixed-model lean production system that is presented addresses the manufacture of a specific subset of rotors that share a relatively common production process.

The technical function of a rotor is to provide thermodynamic expansion or compression of the air which pressurizes and cools the aircraft cabin. To familiarize the reader with their use in a typical aircraft air conditioning system, Figure 13 shows a schematic of the Boeing 777 air conditioning system. The 777 air cycle machine is shown at the bottom of the schematic. This air cycle machine has four rotational components: a fan, a compression rotor and two turbine rotors, labeled F, C, T1, and T2, respectively. Note that while their differences are important from a technical standpoint, fans and rotors (both compression and expansion) are manufactured using the same high-level process, so they will all be grouped into the generic term "rotor" from this point.
forward (regardless of whether the hardware is actually a fan or rotor, and regardless of whether it is in the subset of hardware that is addressed by the lean system or not).

As mentioned, rotors are part of a larger assembly called the air cycle machine, and the air cycle machine is a component of the larger air conditioning system, or "pack". **Figure 14** is a schematic showing the manufacturing process flow up to the air conditioning pack. Notice that there are numerous levels of in-house manufactured and purchased parts that support the end pack assembly.

Hamilton Sundstrand over the past two to three years has implemented lean manufacturing principles in various areas of the air conditioning system manufacture, including pack assembly, valve assembly and heat exchanger fabrication. Ultimately, however, all in-house manufactured parts need to be produced in a lean fashion in order to maximally reduce inventories and achieve a consistent and reliable on-time build and delivery of the packs. That is, a single component such as a rotor can conceivably prevent the pack from being assembled if the rotor is not produced and available on time. In order to buffer for this, Hamilton Sundstrand has traditionally held many tens of thousands of dollars of inventory (equivalent to over 1,000 pieces on average of work in process inventory in the rotor cell at any given time in 2003).

In addition to being used in-house, rotors are replaced on in-service aircraft on a regular basis, and therefore have high demand as spare parts. In fact, rotor demand for spares is about an order of magnitude greater than rotor demand for air cycle machine assembly. On-time delivery to the spare parts customers is, of course, very important.

The motivation and objective, therefore, of this project is to reduce inventories and improve on-time delivery and lead time of the rotor to the internal ACM assembly
customer as well as the external spare parts customers. Another motivation for this project concerns the overall strategic plans for the factory. The senior management of the factory developed a plan to implement a lean production line for heat exchangers. This plan would require the heat exchanger line to occupy an area of the factory where rotors are currently produced. Therefore, an additional motivation was to move rotors to a different area of the factory such that the heat exchanger line could be developed.
Figure 13: Air Conditioning Pack Schematic for Boeing 777
Figure 14: Simplified Diagram of Air Conditioning System Assemblies

Pack Assembly

- Heat Exchanger
- H/X Weldments
- H/X Core
- H/X Fin, Parting Sheets

Air Cycle Machine

- Rotors, Fans
- Shafts, Discs
- Housing

Valve Assemblies

- Valve Assemblies
- Valve Housings

Raw Materials, Castings, Forgings, Purchased Details
4.2 A Brief Explanation of Rotor Manufacturing

Rotors can be categorized by their material (aluminum, titanium or steel), size (large or small), and assembly (one-piece or two-piece). At a high level, all rotors have roughly the same manufacturing process. At a detailed level, however, a part number can have specific manufacturing requirements that differ from other part numbers.

All rotors begin as bar stock or forgings. The first step is to turn the blanks on a CNC lathe where 80% - 90% of the part features are defined. Next, a CNC mill cuts the rotor blades. Generally the rotors are then inspected on a coordinate measuring machine (CMM) before continuing. Individual machining requirements following CMM inspection then vary by part number. The rotor may or may not go through the following additional processes: deburring, honing, additional turning, additional milling, drilling, grinding (ID and/or OD), glass bead peening, balancing, spinning, anodization, fluorescent penetrant inspection, part number marking, assembly, and final inspection.

**Figure 15** shows various large compression, expansion and fan rotors. **Figure 16** shows two small rotors in the stages of raw material, after turning, and after blade milling (and deburring). **Figure 17** through **Figure 19** show close-up photos of these three stages.
Figure 15: Various Large Aluminum Rotors

Figure 16: Two Small Rotors at Three Stages of Manufacture

Figure 17: Rotor Forging and Bar Stock
As will be described in a subsequent section, this project focused on the production of single-piece aluminum rotors, both large and small, like those shown in Figure 15 and Figure 19. As mentioned above, the first step in the production of rotors is to turn the bar stock or forging. For aluminum rotors this happens on one of two large Okuma lathes. These lathes are highly efficient from a mass production standpoint; they are twin-spindle machines capable of holding two pieces and automatically transferring a piece from one chuck to the other such that both sides of the stock can be machined with minimal operator input. They cut at high speeds, typically only a few minutes cutting time per piece after the machine is properly adjusted. They are also very high precision machines, capable of holding grinding-level tolerances on the order of tenths of
thousandths of an inch. For all their upside, however, they require fairly long setups. Changing over from one part number to another typically takes on the order of one to three hours. It should be noted that when the machines were purchased, setup was many hours longer. Hamilton Sundstrand invested in setup reduction in the past to achieve today’s standard of one to three hours.

The second step in the production process is milling the blades. As Figure 15 and Figure 19 show, the blades have rather complex curvature. The gaps between individual blades can be 1/8” or less, requiring fairly small ball-end mills for cutting tools. The primary machines used for cutting the blades are two Matsuura MAM-72 flexible machining centers. The MAMs are capable of completely unattended operation. Each has up to 40 individual pallets on which the operator loads parts waiting to be cut. The machine automatically transfers a waiting piece into the cutting area, loads the program, and begins cutting. These machines, unlike the lathes, have zero “internal” setup, or setup that has to occur while the machine and part are waiting. All loading, unloading, and programming can occur “externally” while another piece is being cut, theoretically keeping cutting time as high as possible. However, as opposed to the lathes, because of the geometric complexity of the blades, the milling time per piece is on the order of one to two hours, rather than a few minutes.

As mentioned, there are numerous additional secondary operations that can be required after blade milling. Based on observation and anecdotal evidence from managers and operators alike, the secondary operations contribute a small fraction of total production lead time and inventory. Therefore, they will not be explained in detail.
4.3 Description of the Problem and Existing State

"An undefined problem has an infinite number of solutions"

Robert A. Humphrey

This section presents typical metrics for the rotor manufacturing cell. Delivery metrics, such as on-time delivery percentage and lead time, typically perform below target, though performance metrics such as quality, cost, and safety, are excellent. Inventory in the cell is generally on-target with the cell's objective. Five main reasons are believed to be responsible for poor delivery performance: the physical layout of the area, the use of a standard cost accounting system, reliance on economic lot quantity to determine batch sizes, volatility in demand, and utilization of certain equipment. The subsections that follow will explore each of these areas in detail.

**Figure 20** through **Figure 25** show the six metrics Hamilton Sundstrand uses throughout their operations to gauge performance, commonly referred to as the “six-pack.” Notice that inventory is generally on-target with commitment, but has not fallen significantly from 2002. On-time delivery (which is measured to Hamilton Sundstrand’s internal customers) is generally well below commitment, hovering at only 60% during the last half of 2003. Order lead time is generally longer than commitment, reaching a peak of 37 days, more than two-times as long as the committed lead time. Product cost is consistently better than commitment, averaging about 85% of committed cost. Quality, in the form of scrap, rework and repair dollars, is also better than commitment and is significantly improved over the past few years. Finally, safety is perfect, with zero OSHA recordable incidents for 2003.
The consequence of missing an on-time delivery commitment depends on whether the customer is the ACM assembly cell or the spares organization. If the customer is the ACM assembly cell, then a late rotor can conceivably delay assembly and conceivably delay delivery of the air conditioning pack to the end customer (such as Boeing). In reality, this never happens as Hamilton Sundstrand buffers their MRP planning system to accommodate late rotor deliveries (and other late part deliveries).

The formal work order in MRP for air conditioning assembly is advanced (anywhere from a few days to two weeks) ahead of the true need date. For example, if an air conditioning pack is truly scheduled to be delivered on March 15, MRP will show the need date as early as March 1 and the due dates for all the subassemblies and parts (including rotors) will be based off March 1. In addition, buffer time is typically added to the planned lead time at each level. For example, if an ACM typically requires three days to be assembled, MRP will schedule the rotor due date to be, for example, five days ahead of the ACM need date. With these two sets of buffers, it is next to impossible that a delayed rotor will impact on-time delivery of a pack to a customer. The downside of this padding, of course, is waste in the form of excess inventory at a significant cost. It should be noted, however, that the time buffers are reviewed periodically and reduced as improvements are made. Overall, Hamilton Sundstrand has been able to reduce the time buffers and therefore lower total inventory levels in the factory over the past few years.

Recall that the vast majority of rotors manufactured are destined not for the ACM assembly cell, but for the spare parts organization. The spares organization maintains a stock of rotor inventory that is based on historical and projected demand from their end customers (such as the US Air Force or United Airlines). If their stock is depleted for
some reason, then missing a rotor delivery commitment may impact the end-use customer. Most often, however, the rotor cell deliveries are merely used to restock the spares warehouse.

The consequences of missing other commitments in the six-pack are less tangible and corrective action requires a case-by-case evaluation. Significantly exceeding product cost or quality targets, for example, typically prompts a root-cause investigation.

**Figure 20: Rotor Cell Inventory**

**Cell Inventory**

2003 Mech Mfg-AMS-ACM-Rotor Cell

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**Definitions**

- **Inventory $ (000)**: The dollar value, at standard cost, of POJ and work-in-process inventory with the cell.
Figure 21: Rotor Cell On-Time Delivery Percentage

Cell On Time Delivery

2003 Mech Mfg-AMS-ACM-Rotor Cell

Goal = 96%
Measures On Time to the Day

On-Time = The quantity of parts that were delivered to Customer (external or other cell) on-time to that Customers' specific need date (demand) divided by the quantity of parts that were due. Expressed as a percentage on-time.

Definitions

Figure 22: Rotor Cell Order Cycle Time

Manufacturing Order Cycle Time

2003 Mech Mfg-AMS-ACM-Rotor Cell

Goal = 13.4

Favorable Performance is Indicated by:
Lower cycle time.

Definitions

Mfg Cycle Time = The number of shop days (excludes weekends and holidays) from release of part to the stocking of that part. The monthly reporting point is an average of all parts delivered in that month.
Figure 23: Rotor Cell Product Cost Index

**Product Cost Index**
Without Burden Variance

2003 Mech Mfg-AMS-ACM-Rotor Cell

Goal = 100%

Favorable Performance is indicated by:
100% is meeting plan, lower is better than plan, higher is worse than plan.

Definitions
Product Cost Index = The actual hours charged to production work orders divided by the standard hours allowed for those work orders including planned inspection and planned variation from standard.

Figure 24: Rotor Cell Quality

**Quality (Scrap, Rework, Repair)**

2003 Mech Mfg-AMS-ACM-Rotor Cell

Favorable Performance is indicated by:
Lower SRR expense dollars.

Definitions
SRR = The expense (in dollars) charged to scrap, rework, and repair of parts to either scrap or bring parts into specification.
4.3.1 Existing Layout

From March to September, 1999, Hamilton Sundstrand consolidated all of the Windsor Locks mechanical operations manufacturing cells into one building. Space in the single building was a constraint, and the time allocated for planning and executing the consolidation was limited. As a result, not all manufacturing cells were laid out in what would now be considered an optimal fashion.

The consequences of the sub-optimal layout are excess inventory and poor material flow, as evidenced by non-sequential arrangement of equipment and measured by distance traveled. Sequential operations are not necessarily located near one another, which reduces communication between workers and hampers feedback on quality issues. The lack of co-location also means that workers are not as easily trained on multiple
pieces of equipment. This reduces the flexibility of the workforce to respond to unplanned and planned operator absences. Also, given that the cell is mixed-model and different part numbers may have different routings, it becomes a daily task to track and locate parts. If the cell were laid out in such a manner that most parts could flow in a forward direction only, this non-value-added task could be reduced or eliminated.

**Figure 26** shows a facilities layout of the existing rotor manufacturing cell. Superimposed is the routing for a typical high-volume rotor. Each dot represents a manufacturing process. Notice the lack of any sense of product flow whatsoever. Note also that the machines in the diagram that are not involved in the production of this part number are used for producing other rotor part numbers. The many pieces of equipment in the cell should give the reader a sense of the complexity of managing an area with varying production processes.
Figure 26: Existing Cell Layout and Routing for a Typical High-Volume Part

1) Draw raw materials
2) Mark raw materials
3) Turn
4) Mill
5) CMM / Inspect
6) Secondary process
7) Secondary process
8) Secondary process
9) Secondary process
10) Secondary process
11) Secondary process
12) Secondary process
13) Secondary process
14) Secondary process
15) Secondary process
16) Secondary process
17) Deliver to customer

End - Deliver to customer

External cell process

Start - Raw Materials
4.3.2 Lot Size Policy and Cost Accounting

Like many manufacturers, Hamilton Sundstrand chooses to measure manufacturing cost performance against the “standard cost” of the product. Standard cost consists of the raw material cost, costs of direct labor, costs of indirect labor, inventory carrying costs, and overhead. Direct labor at each process step is the cost incurred for an operator to run the part through the machine, in other words the chip cutting time multiplied by the labor rate. Indirect labor consists of the labor required for setting up machines. This cost is amortized across all products in a batch since a setup for any given machine only occurs once per batch. A standard is established based on how much time it should take to produce a product (including setup), and actual time is measured as favorable or unfavorable variance to the standard.

An overhead percentage is calculated each year based on historical data and planned activities for the year. The overhead rate includes the cost of support staff (salaried employees such as manufacturing engineers, shop floor control, and production planners), overtime premium, facility moves, machine maintenance, floor space and utilities, the cost of direct labor charging indirect (i.e. hourly employees charging time for clean-up, preventive-maintenance, meetings, etc), and scrap, rework and repair. In the short-run, the overhead rate is essentially fixed, though actual measured overhead can have favorable or unfavorable variance to the standard cost of the product just as direct labor can have favorable or unfavorable variance. In the long-run, the overhead rate is adjusted and presumably can be reduced through improvements such as reducing square footage.
To minimize standard cost, then, all five elements of the cost equation (raw material, direct labor, indirect labor, inventory carrying costs, and overhead) should be minimized. Consider that raw material costs are essentially fixed. Of course, a new supplier can be chosen, but this is a strategic decision rather than a production decision. This leaves manufacturing managers with four cost elements to try to minimize: direct labor costs, indirect labor costs, overhead, and inventory carrying costs. Lowering direct labor costs can be achieved through efficiency improvements: faster or more efficient chip cutting, reducing the number of required operations, etc. Reducing overhead can be achieved through either shorter-term actions (such as reducing scrap, rework and repair), or longer-term actions (such as reducing support staff). Reducing indirect labor costs and inventory carrying costs is a little more complicated.

One approach to minimizing these two elements is to use the economic lot quantity (ELQ). The ELQ, first published by F.W. Harris\textsuperscript{26} in 1913 and widely popularized by R. H. Wilson\textsuperscript{27} in 1934, is used at Hamilton Sundstrand to determine the production lot size for each rotor part number. The ELQ states that for any batch of parts, "there is a fixed preparation cost per batch. The preparation cost per part falls exponentially as the batch quantities are increased, and as this fixed preparation cost is spread over more and more parts."\textsuperscript{28} In other words, a larger batch size will amortize the costs of setup across more and more parts.

On the other hand, there is a linear relationship between the lot size and the holding cost of the inventory. Figure 27 presents the equation for ELQ and shows this tradeoff in graphical format. According to Harris, the combined effect of these two cost curves produces a lot size for which there is a lowest total cost, the ELQ. Harris believed that for minimum production cost, all items produced in factories should be made in their own individually-calculated economic lot quantities.

In line with Harris’ theorem, Hamilton Sundstrand uses the ELQ to determine the production batch size for each individual part number in the rotor cell. They also use the ELQ to allocate the indirect cost portion of the standard product cost to each part in the batch. That is, standard setups are amortized across the economic lot quantity for each part number in order to determine the standard cost of each part.

**Figure 27: Economic Lot Quantity Formula and Diagram**

\[
ELQ = \sqrt{\frac{2 \times \text{(annual units)} \times \text{(setup cost)}}{\text{annual carrying cost per unit}}}
\]

*Economic Lot Quantity*

---

4.3.2.1 Theoretical Objections to the ELQ

There are a number of objections to using the ELQ. First, it is a sub-optimal theorem. As John L. Burbidge, the widely renowned British scholar of production control says quite elegantly, "it is a typical example of suboptimization which breaks the gestalt law attributed to Aristotle. The choice of hundreds of different optimum values (one for each part,) which ignores the effect of all these choices on the total system cannot possibly find a true optimum for the system as a whole."\textsuperscript{30} Burbidge's reasoning is extremely profound and the reader should take a moment to think about it. In essence, Burbidge is saying that the ELQ does not consider the impact of batch sizes on other elements of the system, such as product flow, cycle time, and the ability to deliver parts on-time. It only optimizes one measure of cost.

A paper by John Betts and Robert Johnston of Monash University (Australia) and the University of Melbourne (Australia), respectively, echoes this sentiment. Betts and Johnston note that the ELQ does not satisfactorily answer the question of how many parts to produce in a complex business environment. In particular, in manufacturing it is "often assumed that batch sizing decisions can be made for an individual part in isolation from the influence of decisions about other volatility of the company's fortunes and exposure to the risk of failure. (T)he consequential effect of external factors, such as . . . volatility of customer demand (can) not be adequately represented in analytical formulation."\textsuperscript{31}

Professor Burbidge notes another deficiency of the theory in that it “is based on the use of an extremely inefficient concept of the batch quantity. There are many ways in which parts can be combined into batches for convenience of production. The four most important ways for (production control) are:

1. “*the order quantity* (\(OQ\)) or the number of parts authorized for production by an order;
2. “*the run quantity* (\(RQ\)) or the quantity of a particular part produced on a machine before changing to make some other part;
3. “*the set-up quantity* (\(SQ\)) or the quantity of parts, not necessarily all the same, which are produced on a machine before changing the tooling set-up;
4. “*the transfer quantity* (\(TQ\)) or the quantity of parts transferred as a batch between two machines or other work centres which carry out successive operations on the part.

“It is highly desirable that the different parameters should retain their independence, so that, one can for example, increase set-up quantities and reduce run quantities at the same time. In (ELQ) theory, all these four types of batch quantity are treated as a single parameter called the *batch quantity* (or lot size), and they are changed as a single unit. This makes it impossible to achieve the advantages which are obtainable when the four constituent parameters retain their independence.”\(^{32}\)

Thirdly, the ELQ formula assumes that setup costs depend only on the amount of time needed for setup. That is, Setup cost ($) = Setup Time (hours) * Billing Rate ($/hour), and the billing rate is assumed constant across all machines in the total process.

---

In fact, the billing rate should be treated as a variable since setup costs are capacity
dependent. On a machine that is a true bottleneck (from a Theory of Constraints
standpoint), any downtime resulting from setup is lost output. The value of this time is
greater than the value of time on a non-bottleneck machine. Therefore, the value per unit
time of a setup depends on the capacity utilization of the piece of equipment being set up.
The ELQ treats all setup cost rates as equal, which is inaccurate.

Finally, there are a number of assumptions made in the derivation of the ELQ
which rarely hold in the real world. The first, and most important assumption, is that
demand is known and steady. In the aerospace industry one could argue that demand is
known many months out since the production lead time of aircraft is very long. In a
volatile economy, that is not necessarily the case. During the author’s internship, there
were a number of instances where orders for air conditioning packs (and therefore the
associated rotors) were canceled a few weeks before the scheduled delivery date. Also,
rotors have a large percentage of sales that go to aftermarket spares customers. This
demand is not known with complete certainty. More importantly, however, is that the
demand for rotors, especially from spares, is extremely variable. As will be discussed in
Section 4.3.3, rotor demand is not constant and in fact commonly fluctuates by 50% or
more from month-to-month. This fluctuation places serious doubt into the validity of
using the ELQ for determining appropriate batch sizes.

4.3.2.2 Practical Objections to the ELQ

Large batch sizes coupled with a push-production system can have a profound
impact on product flow. Large batch sizes result in high total lead times, excess
inventory, production greater than demand, difficulty responding to changing customer
demand, and other problems. Lean manufacturing emphasizes the end objective of achieving a batch size of one, as this provides the lowest possible inventory and greatest production flexibility when achieved in a truly lean environment. Of course, a batch size of one may not be achievable in the short-run or even the long-run, but it should be the goal. Anything greater represents waste somewhere in the system. While Hamilton Sundstrand has made a number of wonderful advances toward lean production, they retain the standard cost accounting system (per the direction of UTC Corporate) and its inherent use of ELQ. Standard cost accounting prevents flexibility in establishing appropriate batch sizes and is, in the author’s opinion, the single greatest factor limiting Hamilton Sundstrand’s efforts to achieve truly world-class status as a manufacturer.

To understand the implications of ELQ on production flow, we present a sample of actual ELQ calculations and determine how long it would take a batch of parts of this size to be processed through the first two steps of the rotor manufacturing process – the lathe and the mill. It is first important to note that for quality control and material traceability reasons, batches in general must be kept together. Therefore, the total time is the sum of processing times for each piece in the batch. As each piece in the batch is finished, it is assumed (for now) that it cannot move to the next operation until all pieces in the batch are complete. The five parts presented below represent the five highest-demand parts from November 2003 – May 2004. Table 1 presents the results of how long it would take a batch to be processed through the lathe and mill.
Table 1: Time Calculation for Completion of ELQ Batch Size

<table>
<thead>
<tr>
<th>Part ID</th>
<th>Calculated ELQ</th>
<th>Lathe: setup time per lot (minutes)</th>
<th>Lathe: per piece standard cutting time (minutes)</th>
<th>Mill: per piece standard cutting time (minutes)</th>
<th>Total Cutting Time for Batch (= ELQ * (Lathe + Mill Standard Cutting Time))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part #1</td>
<td>62</td>
<td>111</td>
<td>6.9</td>
<td>92</td>
<td>102 hours</td>
</tr>
<tr>
<td>Part #2</td>
<td>64</td>
<td>140</td>
<td>9.5</td>
<td>143</td>
<td>163 hours</td>
</tr>
<tr>
<td>Part #3</td>
<td>68</td>
<td>130</td>
<td>7.9</td>
<td>66</td>
<td>84 hours</td>
</tr>
<tr>
<td>Part #4</td>
<td>71</td>
<td>126</td>
<td>7.7</td>
<td>66</td>
<td>87 hours</td>
</tr>
<tr>
<td>Part #5</td>
<td>51</td>
<td>131</td>
<td>9.2</td>
<td>43</td>
<td>44 hours</td>
</tr>
</tbody>
</table>

In fairness, because these products are the highest-demand products, their ELQ will generally be larger than lower-demand products, holding setup costs and unit costs constant. But even in the best case of the parts chosen above, a batch of Part #5’s will take nearly two days to be turned and milled! The vast majority of that time is spent in the mill (for instance 92 minutes per part milling versus 6.9 minutes per part turning for Part #1). During this time no other part type can be produced without interrupting the batch (and recall that parts will not move to the next step until the batch is complete). This is a huge barrier to product flow.

Now, Hamilton Sundstrand does in fact recognize this problem and they attempt to handle it by adjusting the ELQ. On a yearly basis Hamilton Sundstrand calculates the theoretical ELQ, but then adjusts it to a more “reasonable” number based on what they chose the previous year and intuition. Table 2 presents, for the same five part numbers, the calculated ELQ, the actual lot size chosen after adjustment, and the time it would take to turn and mill the product with the adjusted lot size.
Table 2: Time Calculation for Completion Using Adjusted Lot Size

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Calculated ELQ</th>
<th>Adjusted Lot Size for 2004</th>
<th>Total Completion Time for Batch (using adjusted lot size)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part #1</td>
<td>62</td>
<td>20</td>
<td>33 hours</td>
</tr>
<tr>
<td>Part #2</td>
<td>64</td>
<td>15</td>
<td>38 hours</td>
</tr>
<tr>
<td>Part #3</td>
<td>68</td>
<td>12</td>
<td>15 hours</td>
</tr>
<tr>
<td>Part #4</td>
<td>71</td>
<td>15</td>
<td>18 hours</td>
</tr>
<tr>
<td>Part #5</td>
<td>51</td>
<td>15</td>
<td>13 hours</td>
</tr>
</tbody>
</table>

After batch size adjustment, these five part numbers take at best 13 hours and at worst 38 hours to complete a full batch of turning and milling. Again, milling is the vast majority of the total time (milling accounts for more than 30 of the 33 total hours for Part #1, for example; setup on the lathe for this part will add an additional two hours to the batch; there is no setup required for the mill). And again, without interrupting the batch that occupies the lathe or mill, no other part type can be produced while one batch is in progress.

While the adjusted ELQ’s are a vast improvement to cycle time over the calculated ELQ’s, they still appear to be unacceptable from a product flow, production lead time, inventory, and on-time delivery standpoint, as evidenced by the actions the foreman has to take to deliver parts on-time. In practice, the foreman of the rotor area has to manipulate the system in order to achieve his monthly production targets. The way he does this is to “split-off” batches of product as they are completed at the mills. For example, Part #4, with a batch size of 15, could be split into three batches of five pieces at the mill. As soon as five are completed, they are split-off into their own batch to proceed to the next step in the production process.
The consequences of operating this way are a triplication of quality control and material traceability paperwork, and a likely increase in measured cost. The standard part cost is based on a lot size of 15. Operating with a lot size of 5 means that downstream operations cannot amortize their setups across as many pieces. This incurs unfavorable variance to the standard cost. Clearly the foreman is in a tough position: either operate to the ELQ to keep costs low but have difficulty achieving on-time delivery, or have a higher probability of delivering the product on-time but do so at higher perceived cost.

An astute reader would question how this statement could be true since Figure 23 shows the cell’s cost performance routinely beating standard cost. The apparent contradiction can probably be explained by worker productivity. All of the operators in the cell are very skilled, with most (if not all) having greater than 20 years experience. They have gone beyond the “average” worker’s learning curve and are able, therefore, to routinely produce at a rate that exceeds the standard that is based on this “average” operator. In fact, it is not uncommon for them to operate at 160% - 180% of the standard. In other words, an operation that has a twenty-minute standard might be completed in twelve minutes. Thus, even though the batch sizes are reduced, which increases the component of standard cost associated with setups, this is offset by lower costs associated with direct labor. If the cell were to be replaced with new operators, it is highly unlikely that they would be able to perform above the standard. In this scenario, actual cost would likely be higher than standard if batches were split into smaller sizes to promote flow.

To summarize so far, Hamilton Sundstrand calculates an ELQ for each part number on a yearly basis. The calculated ELQ, in a standard cost accounting environment, provides the lowest combination of setup costs and inventory carrying.
costs. Yet the calculated ELQ’s are so large that they make product flow and on-time delivery impossible. In order to compensate for this, Hamilton Sundstrand reduces the calculated ELQ’s to a more reasonable number. Still, however, the rotor foreman must manipulate the system by splitting off batches in order to achieve on-time delivery for at least some of his parts. He does this at the expense of measured product cost, but fortunately the experienced operators in the cell compensate for the smaller batch sizes. Note also that even with batch splitting, on-time delivery for the cell as a whole is still only about 60% and production lead time is up to two times greater than the committed lead time.

In short, it appears that the use of a single batch size calculated for each part number in the line is, as John Burbidge notes, suboptimal for the line given the dramatically different modes of operation of the lathe and mill at the front of the line. **Figure 28** illustrates why this is so. Essentially no batch size provides a satisfactory balance between setup and batch cycle time on the lathe, and batch cycle time on the mill. Very small batch sizes will make the apparent cost of the lathe very high due to the setup time on the lathe, whereas a large batch size will make product flow very poor through the mill and downstream operations. Clearly, a single ELQ for each part in the rotor line is inefficient. From an ideal product-flow standpoint, each part would have a batch size calculated for each operation in the line. This system would, of course, be so difficult to manage and coordinate that it is not practical.
In summary, ELQ along with standard cost, drive behavior contrary to that desired in a lean production system. They favor operation in a mass production environment and are nearly meaningless to single piece flow. Different measures of productivity and cost are available, but they would require a large-scale change to the accounting systems, possibly all the way to UTC Corporate. This was not in the scope of the internship. Therefore, any potential solutions for the rotor cell will have to be done by adapting lot sizes within the confines of standard cost, realizing that the solution will not be ideal and will probably not achieve the greatest possible lead time and inventory reductions.

4.3.3 Demand Profile

Another factor contributing to poor on-time delivery and long lead times in the rotor cell is uneven demand. Uneven demand leads to poor cell performance because it
becomes very difficult to plan and execute appropriately when demand fluctuates. This is especially true in a mixed-model cell where machining and setup times can vary substantially between part numbers. With high fluctuation from month-to-month or week-to-week it becomes difficult to establish the Takt time and perform to it. Capacity can become an issue, as can staffing. In short, an efficient lean system depends on stable known demand.

The following tables illustrate the level of demand fluctuation. Presented are the ten aluminum rotors with highest total demand from November 2003 to May 2004. These ten rotors represent about 60% of the total demand for that time period. Table 3 shows the actual demand for each part number in each month from November to May, while Table 4 presents the percentage change in demand for each part number from month to month.

**Table 3: Demand Profile for 10 Highest Volume Parts**

<table>
<thead>
<tr>
<th>Part ID</th>
<th>Nov 03</th>
<th>Dec 03</th>
<th>Jan 04</th>
<th>Feb 04</th>
<th>Mar 04</th>
<th>Apr 04</th>
<th>May 04</th>
<th>Total</th>
<th>Avg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part #1</td>
<td>104</td>
<td>115</td>
<td>163</td>
<td>44</td>
<td>18</td>
<td>37</td>
<td>16</td>
<td>497</td>
<td>71.0</td>
</tr>
<tr>
<td>Part #2</td>
<td>34</td>
<td>128</td>
<td>74</td>
<td>60</td>
<td>42</td>
<td>34</td>
<td>32</td>
<td>404</td>
<td>57.7</td>
</tr>
<tr>
<td>Part #3</td>
<td>54</td>
<td>59</td>
<td>110</td>
<td>32</td>
<td>34</td>
<td>66</td>
<td>32</td>
<td>387</td>
<td>55.3</td>
</tr>
<tr>
<td>Part #4</td>
<td>70</td>
<td>105</td>
<td>30</td>
<td>19</td>
<td>4</td>
<td>40</td>
<td>16</td>
<td>284</td>
<td>40.6</td>
</tr>
<tr>
<td>Part #5</td>
<td>39</td>
<td>84</td>
<td>18</td>
<td>17</td>
<td>4</td>
<td>16</td>
<td>14</td>
<td>192</td>
<td>27.4</td>
</tr>
<tr>
<td>Part #6</td>
<td>24</td>
<td>52</td>
<td>19</td>
<td>39</td>
<td>7</td>
<td>44</td>
<td>4</td>
<td>189</td>
<td>27.0</td>
</tr>
<tr>
<td>Part #7</td>
<td>31</td>
<td>42</td>
<td>25</td>
<td>17</td>
<td>15</td>
<td>40</td>
<td>14</td>
<td>184</td>
<td>26.3</td>
</tr>
<tr>
<td>Part #8</td>
<td>0</td>
<td>91</td>
<td>35</td>
<td>0</td>
<td>0</td>
<td>24</td>
<td>18</td>
<td>168</td>
<td>24.0</td>
</tr>
<tr>
<td>Part #9</td>
<td>18</td>
<td>23</td>
<td>27</td>
<td>32</td>
<td>35</td>
<td>19</td>
<td>14</td>
<td>168</td>
<td>24.0</td>
</tr>
<tr>
<td>Part #10</td>
<td>8</td>
<td>17</td>
<td>27</td>
<td>19</td>
<td>35</td>
<td>3</td>
<td>14</td>
<td>123</td>
<td>17.6</td>
</tr>
</tbody>
</table>
Table 4: Percentage Change in Demand from Previous Month

<table>
<thead>
<tr>
<th>Part ID</th>
<th>Nov 03</th>
<th>Dec 03</th>
<th>Jan 04</th>
<th>Feb 04</th>
<th>Mar 04</th>
<th>Apr 04</th>
<th>May 04</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part #1</td>
<td>N/A</td>
<td>11%</td>
<td>42%</td>
<td>-73%</td>
<td>-59%</td>
<td>106%</td>
<td>-57%</td>
</tr>
<tr>
<td>Part #2</td>
<td>N/A</td>
<td>276%</td>
<td>-42%</td>
<td>-19%</td>
<td>-30%</td>
<td>-19%</td>
<td>6%</td>
</tr>
<tr>
<td>Part #3</td>
<td>N/A</td>
<td>9%</td>
<td>86%</td>
<td>-71%</td>
<td>6%</td>
<td>94%</td>
<td>-52%</td>
</tr>
<tr>
<td>Part #4</td>
<td>N/A</td>
<td>50%</td>
<td>-71%</td>
<td>-37%</td>
<td>-79%</td>
<td>900%</td>
<td>-60%</td>
</tr>
<tr>
<td>Part #5</td>
<td>N/A</td>
<td>115%</td>
<td>-79%</td>
<td>-6%</td>
<td>-76%</td>
<td>300%</td>
<td>-13%</td>
</tr>
<tr>
<td>Part #6</td>
<td>N/A</td>
<td>117%</td>
<td>-63%</td>
<td>105%</td>
<td>-82%</td>
<td>529%</td>
<td>-91%</td>
</tr>
<tr>
<td>Part #7</td>
<td>N/A</td>
<td>35%</td>
<td>-40%</td>
<td>-32%</td>
<td>-12%</td>
<td>167%</td>
<td>-65%</td>
</tr>
<tr>
<td>Part #8</td>
<td>N/A</td>
<td>-62%</td>
<td>-100%</td>
<td>0%</td>
<td>∞</td>
<td>∞</td>
<td>-25%</td>
</tr>
<tr>
<td>Part #9</td>
<td>N/A</td>
<td>28%</td>
<td>17%</td>
<td>19%</td>
<td>9%</td>
<td>-46%</td>
<td>-26%</td>
</tr>
<tr>
<td>Part #10</td>
<td>N/A</td>
<td>113%</td>
<td>59%</td>
<td>-30%</td>
<td>84%</td>
<td>-91%</td>
<td>367%</td>
</tr>
</tbody>
</table>

With the exception of perhaps Part #9, each of the ten highest-volume parts experiences large fluctuation in demand from month to month. One of the first rules of supply chain planning and forecasting is to aggregate demand as much as possible across individual products in order to “risk pool.” Unfortunately, this is not easily done with rotors as each part number is different from the next to some degree. Therefore the cell has to cope with this volatility. This will be a major challenge in designing a lean flow line and, as will be seen, will manifest itself in high amounts of buffer inventory.

### 4.3.4 Ability of the MAMs to Flow Product with Limited Pallets

In Section 4.3.3.2 we examined the time required to complete a batch of parts at the Matsuura MAM-72 mills. In reality, this time may be understated. The reason for this has to do with the “pallets” that are available within each mill. The pallets provide the fixturing to hold the turned rotor while the blades are being milled. The fixtures hold the piece through the center spindle. Since most rotor’s spindle diameters and heights are different, there is generally a custom pallet designed for each part number. Of course, there are a few part numbers which are similar and can share a pallet. Table 5 presents a combined matrix of fixture and part numbers for the two Matsuura mills. The matrix

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indicates which part numbers are capable of being machined on each fixture. Notice that most pallets are capable of holding just one part number.

Table 5: MAM Fixtures and Corresponding Part Numbers

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<td>34</td>
<td>33</td>
<td>32</td>
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<tr>
<td>Part #22 Roughing</td>
<td>Part #20</td>
<td>Part #16</td>
<td>Part #19</td>
<td>Part #18</td>
<td>Part #25 Roughing</td>
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<td>Part #12</td>
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<td>31</td>
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<td>26</td>
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<tr>
<td>Part #7</td>
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<td>Open</td>
<td>Open</td>
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<td>Part #8</td>
<td>Part #21</td>
<td>Part #20</td>
<td>Part #50</td>
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<tr>
<td>Open</td>
<td>Open</td>
<td>Part #32</td>
<td>Part #26</td>
<td>Part #26</td>
<td>Part #41</td>
<td>Part #42</td>
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<td>Part #17</td>
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<td>6</td>
<td>5</td>
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<tr>
<td>Part #10 Roughing</td>
<td>Part #24</td>
<td>Part #15</td>
<td>Part #21</td>
<td>Part #34</td>
<td>Part #10 Finishing</td>
<td>Part #10 Finishing</td>
<td>Part #5</td>
<td>Part #25</td>
<td>Part #17 Roughing</td>
<td>Part #17</td>
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<tr>
<td>4</td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Part #31</td>
<td>Part #3</td>
<td>Part #22</td>
<td>Part #6</td>
<td></td>
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</tbody>
</table>

Because of the limited number of pallets available for each part number, it becomes logistically difficult to complete a single batch of parts without interruption by a different part type. For instance, consider a batch of Part #1. Recall this part has the highest demand of any aluminum rotor, it has an adjusted lot size of 20 pieces, and it takes about 92 minutes to mill each piece. Assume that each MAM has a pallet, therefore the batch can be simultaneously processed on both machines. Therefore only 10 pieces need to be completed at each mill to complete the batch. This means in the ideal case the batch should be completed in just over 15 hours (92 minutes per piece * 10 pieces / 60 minutes per hour).
What happens when the operator actually starts to process this batch? Since each MAM has only one pallet capable of holding a Part #1, and since the machine is supposed to run unattended during second and third shift, the operator will load the machine with other part numbers so that the machine can keep cutting chips overnight. In the morning, one each of, say, ten different part numbers will be machined. But only one Part #1 will be completed at each MAM. During the day shift the operator can attend to the machine to unload and reload it with additional Part #1's, but inevitably two-thirds of every day (and the entire weekend) is spent cutting just one piece of multiple batches of different part numbers. This is why a batch will never be completed in the minimum time calculated. Indeed, the evidence of this can be seen at the MAMs. There is always inventory representing half-finished lots of multiple part numbers at the machines. The foreman has to manage the area by hot list to expedite the most overdue batches. Again, for quality control and material traceability reasons, it is not possible to send individual pieces or groups of pieces to the next operation in the line without the rest of the batch. This is the main reason why the foreman has to duplicate paperwork to split off smaller batches as described in Section 4.3.2.2 and possibly incur unfavorable cost variance. He simply cannot wait for the time it would take to complete all twenty parts in a batch.

One way to cope with this situation is to staff the Matsuura’s over the second and third shifts and weekends. Numerous sources, however, disclosed that the cost justification for purchasing these expensive machines included the fact that they can be run unattended (incurring operator time for loading and unloading the parts only, thereby lowering standard cost of the parts) and that they would reduce operator requirements to just one shift.
To be fair, Hamilton Sundstrand did recognize the pallet constraint issue in January 2002 and did purchase additional pallets for select high-volume part numbers such that more than one part per batch could be completed sequentially without operator intervention. But since that time, the demand profile has changed and other parts are now the high demand parts (witness the fact that Part #1, the highest-volume part at the present time, has only one pallet). Hamilton Sundstrand could, and probably should, procure additional pallets for these parts, but that is basically playing a game of catch-up. Any time the demand profile shifts this issue will re-emerge. And, since each machine can only hold 40 pallets total, eventually the pallet capacity will be reached. Of course, a pallet purchased is not necessarily a pallet wasted in the event that the demand profile changes. And, of course, there are ways to improve pallet flexibility, but they are not addressed in this thesis. Instead, the author proposes that a new management system is needed to control the demand through the Matsuura’s. A proposal for this new system will be presented in the subsequent sections.

4.3.5 Summary of the Existing State and its Manifestation into Metrics

The state of the rotor cell today is a product of history. If one were to go back ten years, he would find the rotor cell had many more machines than today with many more operators than today. The batch and queue system generally worked because there was an excess of capacity in almost every process step.

Through the years, facing increased pressure to reduce cost, the cell has evolved substantially. Technological improvements have allowed process steps to be eliminated (grinding, for example, is now largely eliminated because the new lathes can achieve incredibly tight tolerances). Technical improvements have also allowed equipment and
people to be eliminated (a single lathe with automatic chuck transfer can now do what
two lathes, and two people, used to do; the flexible mills need only a fraction of a person
to attend to them). Other improvements have reduced total processing time substantially.
Through the ACE program, 5s has been implemented, creating a clean, organized factory;
TPM was adopted, improving reliability of the machines and instilling a sense of
ownership among the workers; and quality data is collected to determine the root cause of
problems. All of this effort has improved many of the cell metrics – perfect safety in
2003, costs below standard for the entire year, and quality better than plan for the entire
year.

Yet these improvements have also changed the production landscape. With long
setups, the lathes are best suited for long production runs. But with zero setup, the
MAMs are best suited for lot size of one. The rest of the cell falls somewhere in
between. The cost accounting system was created when the world favored mass
production. Today we favor lean production. A highly variable demand profile becomes
a major problem to on-time delivery as the push to reduce inventory takes out safety
stocks. And the metrics people are measured to conflict with each other – lead time and
on-time delivery suggest smaller batches; low cost suggests larger batches.

While Hamilton Sundstrand’s lean efforts have been noble and largely effective,
there is misalignment within their current production system. The remainder of the
chapter focuses on what is needed to get the system into alignment with the objective of
lean production.
4.4 The Process to Create a Lean Manufacturing System

"The significant problems we have cannot be solved at the same level of thinking with which we created them."

Albert Einstein (attributed)

The steps and activities needed to achieve a lean manufacturing system are generally acknowledged. They include specifying value and identifying the value stream, making the value-creating steps flow, initiating pull, and striving for perfection. This section discusses specific actions that can be taken in the rotor cell to achieve these objectives, and also the limitations that are present in the rotor cell.

4.4.1 Value Specification and Identification

Specifying value from the customers' perspective and identifying the value stream comprise the first step to creating a lean manufacturing system. Specifying value focuses the lean effort on a specific product which meets the customer's needs at a specific price at a specific time. Identifying the value stream exposes the processes or actions that are value-creating, from those that are not value-creating. Of those that are not value-creating, the value stream can often distinguish those that can be immediately eliminated from those that cannot be immediately eliminated because they are currently required in the manufacturing system. Identifying the value stream is achieved by creating a current state and future state map of the manufacturing process. The value stream mapping process for the rotor cell will be discussed in Section 4.5.

34 Ibid, 16.
4.4.2 Creation of Flow

Creating flow is the second step in a lean transformation, and it is probably the most difficult. It can require a complete rearrangement of mental models, challenging our basic assumptions on the most efficient ways of production. Instead of batches being processed within functional areas, flow has us work on a continuous stream of products from start to finish.

There are a number of tools to help create flow. One of the first Americans to take the experiences of companies that implemented some version of the Toyota Production System and present them in a logical, step-by-step strategy was J T. Black of Auburn University. Five years ahead of Lean Thinking, Dr. Black wrote the book The Design of the Factory with a Future in 1991. This book presents 10 steps to creating what he calls “integrated manufacturing production systems (IMPSs).” The first five steps are really about creating flow. It is worthwhile to look at these five steps.

4.4.2.1 Step 1: Form Manufacturing and Assembly Cells

The cell is the heart of an integrated manufacturing system. Production control, quality control, and inventory control become integrated parts of the cell. The cell should be a group of processes designed to make a family of parts in a flexible way, with one-piece movement of parts within the cells, and small-lot movement of parts between cells. Workers within the cell should be multiprocess. Sections 4.6.2 and 4.7.2.2 will discuss how manufacturing cells were designed for rotor production.

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36 Ibid, 7.
4.4.2.2 Step 2: Reduce or Eliminate Setup

The impact of setup reduction on flow and overall cell metrics cannot be overstated. Setups are not a small aspect of the manufacturing process. Reducing setup time is the key to reducing bottlenecks, lowering costs, and improving quality. Setups are, from this perspective, the most critical element of the manufacturing process.37

Arguments against small batch sizes frequently center on the ELQ. The ELQ theory treats set-up time as a constant, however. It reasons that the cost per piece for parts can only be reduced by manufacturing in large batches in order to spread out the cost of setting up.38 Yet set-up is not an invariable constant. Indeed, with setup reduction, manufacturers can build in very small lots for the same cost as a company building in large lots that does not invest in setup reduction. This gives the company producing in small lots a competitive edge in flexibility.39 In essence, with setup reduction, the concept of economic lot size is a non-issue since the sensitivity of cost to batch size approaches zero as setup is reduced to zero!

In general, numerous case studies have shown companies in a wide variety of industries using Shigeo Shingo’s setup reduction process to achieve under-ten-minute setups (an order of magnitude reduction to be used as a goal) on equipment that previously took many hours to setup.40 Many of the companies studied were originally hesitant to invest in setup reduction as they believed their individual circumstances would

make a ten-minute setup impossible. The claim of “it can’t be done here” is apparently very common yet in almost all instances, incorrect.

At Hamilton Sundstrand, extensive setup reduction activities were successfully performed on the lathes when they were purchased and installed, reducing their setup from many hours to the one-to-three hour standard of today. As such, this project did not tackle further setup reduction. Yet since there is undeniable strategic and financial value to ten-minute setups, it is strongly recommended that Hamilton Sundstrand once again examine setup reduction on the lathes. If achieved, a ten-minute setup would provide tremendous flexibility to the rotor line and would dramatically reduce inventory levels. A ten-minute setup would, as described above, eliminate the issue of economic lot size.

Since setup reduction was not initiated during the project, however, a workaround to large lot sizes (driven by one-to-three hour setups) had to be discovered. The workaround uses a supermarket to decouple the lathe operation from downstream operations. While the details will be discussed later, the supermarket will allow smaller batch sizes to be pulled into the mills and downstream operations, while being filled by the lathes in larger batches, thus amortizing their setup. The quantity of inventory in the supermarket will, unfortunately, need to be high until such time that the lathes can be made flexible to the demand signals of the downstream operations (i.e. through setup reduction).

4.4.2.3 Step 3: Integrate Quality Control

The third step in creating flow is to integrate quality control within the cell. The one-at-a-time system within the cell means that the workers not only make product but inspect it before passing it on to the next operation. Every worker has the responsibility
and authority to make the product right the first time and every time.\(^{41}\) Fortunately, UTC’s ACE program instills this process already. The production certification process gives operators the training to inspect their own work and the authorization to do so.

\textbf{4.4.2.4 Step 4: Integrate Preventive Maintenance}

Like integrated quality control, the operators in the cell should be responsible for maintaining the equipment in the cell. The primary goal of this is to prevent failure of equipment before it actually occurs.\(^{42}\) Integrated preventive maintenance not only provides fewer unexpected failures, but it leads to better quality, flexibility, safety, production capability, and even a reduction in inventory through the removal of safety stock.\(^{43}\) Again, fortunately, Hamilton Sundstrand is well-versed in preventive maintenance, as this is a key element of ACE.

\textbf{4.4.2.5 Step 5: Level and Balance}

Black describes the meaning of and the reasons for leveling and balancing. “Leveling is the process of planning and executing an even production schedule. In an ideal situation, a factory would produce an even distribution of products every hour, each day. That is, items would be manufactured every day, and in the same way. Balancing is the method of setting the overall cycle time in order to synchronize the rate of production with the rate of consumption. The principle behind leveling and balancing is simply to regulate production output and final assembly to minimize the demand spikes. Final assembly should not pull products from the upstream... manufacturing cells... in a

\(^{42}\) Ibid, 143.
\(^{43}\) Ibid, 137.
way that causes (them) to fluctuate or peak. Fluctuations cause production planners to set production rates on the upstream processes at the maximum level of the demand spikes. This, of course, results in overproduction and excess inventory – in other words, waste.”

Section 4.3.3 discussed the demand profile that the rotor cell currently faces. Demand fluctuations exceeding 50% from month-to-month are not uncommon due to aftermarket provisioning. Smoothing this volatility is important if the new lean flow line is to operate efficiently and without waste in the form of excess inventories. While this project did not focus on demand smoothing, Hamilton Sundstrand’s future efforts will be doing so.

4.4.2.6 Summary of Creating Flow

This subsection looked at the five elements to create flow, as proposed by J T. Black: form cells, reduce setup, integrate quality control, integrate preventive maintenance, and level and balance. Forming cells will be a major advancement for the rotor process and constitutes a portion of this thesis. Reducing setup would be a tremendous benefit to the new lean flow line, but was not initiated (due to previous set up reduction activities). The steps for integrating quality control and preventive maintenance are well on their way at Hamilton Sundstrand already. Leveling and balancing must be done, and will be done, in the future to further reduce inventories and improve delivery metrics.

4.4.3 Production Based on Pull

The third step in creating a lean manufacturing system is to link production to pull signals. Black calls this step (his 6th and 7th steps) “Integrated Production and Inventory
Control.” A pull signal is simply a cue from a downstream process to an upstream process to begin production of a specific item. In many cases, the pull signal takes the form of a kanban.

The kanban system is a manual (and usually visible) method for controlling production and inventory within a factory. Many people think that a lean manufacturing system is just a kanban system. This is not true. Kanban is simply a production and inventory control subsystem for a lean manufacturing system. As Shingo notes in the following anecdote, kanban can’t be used until the system is lean.

“Now you might think that the Toyota Motor Company is just a company wearing a smart suit (referring to kanban), and you want to buy such a suit for your company. However, if you only buy the kanban subsystem, you soon discover that this suit will not fit your obese, fat body (your manufacturing system) and chaos soon results.”

Before implementing kanban, the manufacturing system must flow and it must be lean such that when a kanban signal is initiated, the manufacturing system can respond to it. When kanban is implemented successfully, it provides the manufacturing system with a visible and simple way to control production (through the issuance of kanban cards) and inventory (by adding or subtracting the number of cards in circulation).

4.4.4 Perfection

The fourth step of creating a lean manufacturing system is perfection. This is the final step, yet the process is never final. The first three steps of lean, when done correctly, tend to create a virtuous cycle such that as flow is improved, additional wastes

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45 Ibid.

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are exposed. And the harder the pull, the more impediments to flow are revealed so they can be removed. Excellence in this never-ending step is presently what separates Toyota from the rest of the manufacturing world.

4.4.5 Summary of the Process to Create a Lean Manufacturing System

This section briefly explained the processes to achieve a state of lean manufacturing. The four steps to lean are: specifying and identifying value, creating flow, initiating pull, and perfection. The sequence of these steps is important. It is especially important to create a lean flow system before tying to implement a kanban pull system.

So far we have examined the current state of rotor production, characterized by an inefficient layout, large batch sizes governed by the ELQ, throughput problems at the blade mills, and highly variable demand. In addition, we have examined the process to achieve a state of lean manufacturing. We now turn our attention to applying these processes to the rotor cell. Value stream mapping is used to specify value and to create the vision for the new production system. A layout is designed that incorporates cellular manufacturing. And a discrete-event simulation is created to analyze the complexities inherent in a low-volume mixed-model production line.

4.5 Value Stream Mapping – Specifying and Identifying Value

The system redesign process begins with a value stream event to discover the current state and devise the future state. This step is essential to determining where waste exists and what changes are necessary to eliminate it. The future state map also provides

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a guide for defining elements of the lean value stream strategy, including where continuous flow can exist, which steps to choose to schedule production, whether or not supermarkets will be needed to segregate dissimilar processes, and whether the finished goods should be built directly to shipping or to a finished goods supermarket.

4.5.1 Current State Map

Ideally, the value stream will be mapped for a part family. Choosing a part family in the rotor cell was difficult, as very few parts share identical process routings. Instead, a single part was chosen that contains all potential process steps for single-piece aluminum rotors. A picture of the actual hand-drawn current state map created at the beginning of the rotor project is shown in Figure 29 and Figure 30. Refer to Appendix B or Learning to See for an explanation of the symbols used in value stream mapping.

The rotor cell current state map shows characteristics that are very common for push-process MRP-controlled manufacturing systems. These characteristics include inventory between each process step, multiple days worth of inventory at some process steps, multiple process steps that are scheduled by production control, long change-over times, and the reliance on hot-lists for expediting. Note also that the current state map shows a production lead time of 28 days while the process lead time is only 309 minutes, or 0.2 days. Including setup time for the batch at each step, process lead time increases to 695 minutes, or 0.5 days. In other words, value-added “hands on” time accounts for a half-day of work, yet the batch and queue production process results in a rotor taking 28 days from start to finish. Implicitly, this means the ratio of value added to non-value added steps is 0.02. Certainly there is room for improvement.

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47 Mike Rother and John Shook, Learning to See, (Brookline, MA: Lean Enterprise Institute, 1998), 58.
Figure 29: Current State Map for Rotor Cell (first-half)
Figure 30: Current State Map for Rotor Cell (second-half)
4.5.2 Future State Map

The actual hand-drawn future state map for the rotor cell is presented in Figure 31 and Figure 32. Recall that the future state map is intended to represent an optimistic outcome that the team believes is realistically achievable. The team should focus on creating a future state that links individual production processes by continuous flow or pull, such that each process gets as close to producing only what its customer(s) need when they need it. In building the future state, the rotor team tried to address the following questions:

1. Will we build to a finished goods supermarket from which the customers pull, or will we build to direct customer demand (i.e. to shipping)?
2. Where can we use continuous flow processing?
3. Will we need to use a supermarket pull system in order to control production of upstream processes?
4. At what single point in the production process will we schedule production? This will be the pacemaker process.
5. What process improvements will be necessary for the value stream to flow as the future state specifies?

In addition to the above questions, the future state map should also answer the following questions listed below. The future state map for the rotor line, however, did not adequately answer the questions, mainly due to the mixed-model nature of the cell.

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48 Ibid, 57.
49 Ibid, 58.
In not adequately answering all the questions, there is therefore some risk that the future state map has missed an important issue.

6. What is the takt time, based on the available working time of the downstream processes that are closest to the customer?

7. How will we level the production mix at the pacemaker process?

8. What increment of work will we consistently release and take away at the pacemaker process?

The future state map addresses the first five questions in the following way.

First, in response to question two, process steps are combined when possible. For example, deburr, hone and lathe are combined into one process step. This means that instead of batch processing through the deburr step, then the hone, then the lathe, single-piece flow should be used between these three steps. This will eliminate inventory between the individual process steps, thereby reducing production lead time.

Second, FIFO (first in first out) lanes are used between process steps that cannot be combined with single piece flow. FIFO will help to regulate what part numbers are processed in what order, and they serve as a visual signal of possible overproduction upstream of the FIFO lane.

Third, flow (either continuous or through the use of FIFO lanes) is achieved all the way back to the blade milling operation. The blade mill, therefore, is the single point in the production chain where production is scheduled (question four).

Fourth, the customer (either spares or ACM assembly) pulls from a supermarket of finished goods inventory (question one). Producing to a supermarket is chosen over
producing directly to “shipping” (i.e. to the spares customer or to the ACM assembly process). The reason for this is because demand volatility is high, the reliability of the lean production system isn’t known \textit{a priori}, and the highest priority is to improve on-time delivery. Of course, the use of a finished goods supermarket comes at the expense of inventory. After the lean production system is implemented and the cell learns what is necessary to further improve lead-time and reliability, the finished goods strategy can be re-evaluated and potentially changed to direct shipping.

Fifth, there are numerous kaizen bursts in the future state map, representing the process improvements required to achieve the future state (in response to question five). For example, under the “Dispatching and Lathe” process step, a kaizen burst says “Training to cut travelers”. What this means is that in the future state the lathe operators will receive signals to begin work by a kanban card instead of being told what to work on by the foreman (who basis his decision on MRP and a hot list). As such, the lathe operators, in the future state, will need to be able to create and issue their own work orders (travelers), and will therefore need training on how to do that.

Finally, and most importantly, production to refill the finished goods supermarket is signaled through the use of a kanban card that is sent \textit{to the blade mills}. Likewise, a supermarket of in-process inventory resides ahead of the blade mill and is replenished by the lathes, answering question three. The supermarket is the most important piece of the future state, and the significance of the strategy cannot be understated. What this allows in the future state is for the batch size of the parts from the mill forward to be different and smaller from that at the lathes. While both batch sizes are still governed by the adjusted ELQ, this strategy will promote flow through the mill and downstream processes
while not significantly increasing standard cost since the long-setup lathes will still amortize their setups over a larger batch size.

The supermarket will, of course, need to be stocked with enough inventory of each part number to last through the queuing time ahead of the lathes in order to make it impossible to starve the downstream mills. The amount of inventory required is calculated by looking at the demand over the replenishment lead time. This will be further explained in Section 4.9.
Figure 31: Future State Map for Rotor Cell (first-half)
Figure 32: Future State Map for Rotor Cell (second-half)
4.6 Initial Analysis to Create Part Families and Machine Sequence

The future state map establishes a vision for what the manufacturing system should look like. The future state is created based on a part family. It determines regions of the manufacturing process where it is possible to achieve single piece flow. Yet there is analysis still required to actually determine the part family and determine the sequence of operations to achieve single piece flow. The next two sections present these analyses.

4.6.1 Line Segmentation and Part Family Identification

The rotor cell is a mixed-model cell, producing about 73 different part numbers. It became clear when preparing for the value stream mapping event that not all parts follow a common process. In fact, most parts are unique in some aspect of their manufacture. In particular, the two-piece rotors could be very difficult to handle in a lean flow line. This is because their manufacturing plan requires multiple trips through certain processes – that is, they do not follow a sequential flow of operations. The new lean flow line will likely have to use a segmentation strategy to separate those parts with “bad flow” from those with “good flow.” In addition, the lines will be segmented based on material. Because of machining coolant differences, steel and titanium parts will be segmented from aluminum parts.

With this basic strategy in mind, the list of 73 parts is segmented into two families: an MRD family and an MRP family (recall that MRD stands for Market Rate of Demand and, along with ACE, is Hamilton Sundstrand’s moniker for lean manufacturing; MRP is of course Materials Resource Planning and is the antithesis to lean manufacturing). The MRD family consists entirely of aluminum parts. They are all
single-piece rotors with the potential for forward flow only. This part of the line will be controlled by kanban card and will use the supermarket strategy as defined in the future state. The MRP family consists of all steel and titanium rotors, as well as those aluminum rotors that are two-piece or have other characteristics in their manufacturing plan that make them less desirable choices for a forward-flow only line. The MRP parts can additionally consist of extremely-low-volume aluminum rotors. The traditional MRP system will continue to be used to manage this part of the line. Note that aluminum parts in the MRP family (such as aluminum two-piece rotors) may still have to be turned and milled on the MRD lathe and mill, but will then continue on the MRP side of the line.

Table 6 presents a break-down of the 73 rotors into different categories, including the two families. For example, of the 73 rotor part numbers, 64 are made of aluminum, and 9 are made of steel or titanium.

Table 6: Rotor Categorizations

(Quantities reflect number of part numbers in each category)

<table>
<thead>
<tr>
<th>Rotor Material</th>
<th>64</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td></td>
</tr>
<tr>
<td>Steel / Titanium</td>
<td>9</td>
</tr>
<tr>
<td>Rotor Size</td>
<td></td>
</tr>
<tr>
<td>Small</td>
<td>49</td>
</tr>
<tr>
<td>Large</td>
<td>24</td>
</tr>
<tr>
<td>Rotor Construction</td>
<td>56</td>
</tr>
<tr>
<td>Single-piece</td>
<td></td>
</tr>
<tr>
<td>Two-piece</td>
<td>17</td>
</tr>
<tr>
<td>Rotor Volume</td>
<td>24</td>
</tr>
<tr>
<td>High-volume (80%)</td>
<td></td>
</tr>
<tr>
<td>Low-volume (20%)</td>
<td>49</td>
</tr>
<tr>
<td>Rotor Routing</td>
<td>37</td>
</tr>
<tr>
<td>Through MRD Line</td>
<td></td>
</tr>
<tr>
<td>Through MRP Line</td>
<td>36</td>
</tr>
<tr>
<td>Simulation Modeling</td>
<td>46</td>
</tr>
<tr>
<td>Modeled in simulation</td>
<td></td>
</tr>
<tr>
<td>Not modeled in simulation</td>
<td>27</td>
</tr>
</tbody>
</table>
Table 7 presents an 80/20 analysis of the rotors by volume. Notice that 24 of the 73 rotors (roughly 1/3) comprise 80% of the cell’s volume. Of these, 17 can be considered MRD parts. All parts classified as MRD make up 80% of the total cell volume.

Table 7: 80/20 Analysis of Part Numbers

<table>
<thead>
<tr>
<th>Part ID</th>
<th>Jul 03 - Mar 04</th>
<th>Grand Total</th>
<th>Percent</th>
<th>Cum Percent</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part #43</td>
<td>20</td>
<td>0.3%</td>
<td>96.2%</td>
<td>2-pc MRP</td>
<td></td>
</tr>
<tr>
<td>Part #44</td>
<td>20</td>
<td>0.3%</td>
<td>96.5%</td>
<td>2-pc MRP</td>
<td></td>
</tr>
<tr>
<td>Part #50</td>
<td>20</td>
<td>0.3%</td>
<td>96.8%</td>
<td>MRD</td>
<td></td>
</tr>
<tr>
<td>Part #49</td>
<td>20</td>
<td>0.3%</td>
<td>97.1%</td>
<td>MRD</td>
<td></td>
</tr>
<tr>
<td>Part #68</td>
<td>19</td>
<td>0.3%</td>
<td>97.4%</td>
<td>Steel</td>
<td></td>
</tr>
<tr>
<td>Part #6</td>
<td>16</td>
<td>0.2%</td>
<td>97.7%</td>
<td>MRD</td>
<td></td>
</tr>
<tr>
<td>Part #56</td>
<td>16</td>
<td>0.2%</td>
<td>97.9%</td>
<td>2-pc MRP</td>
<td></td>
</tr>
<tr>
<td>Part #57</td>
<td>16</td>
<td>0.2%</td>
<td>98.1%</td>
<td>2-pc MRP</td>
<td></td>
</tr>
<tr>
<td>Part #58</td>
<td>16</td>
<td>0.2%</td>
<td>98.4%</td>
<td>2-pc MRP</td>
<td></td>
</tr>
<tr>
<td>Part #41</td>
<td>15</td>
<td>0.2%</td>
<td>98.6%</td>
<td>2-pc MRP</td>
<td></td>
</tr>
<tr>
<td>Part #42</td>
<td>14</td>
<td>0.2%</td>
<td>98.8%</td>
<td>2-pc MRP</td>
<td></td>
</tr>
<tr>
<td>Part #52</td>
<td>10</td>
<td>0.2%</td>
<td>99.0%</td>
<td>2-pc MRP</td>
<td></td>
</tr>
<tr>
<td>Part #46</td>
<td>9</td>
<td>0.1%</td>
<td>99.1%</td>
<td>2-pc MRP</td>
<td></td>
</tr>
<tr>
<td>Part #67</td>
<td>9</td>
<td>0.1%</td>
<td>99.2%</td>
<td>Steel</td>
<td></td>
</tr>
<tr>
<td>Part #59</td>
<td>9</td>
<td>0.1%</td>
<td>99.4%</td>
<td>MRD</td>
<td></td>
</tr>
<tr>
<td>Part #55</td>
<td>8</td>
<td>0.1%</td>
<td>99.5%</td>
<td>Bad flow MRP</td>
<td></td>
</tr>
<tr>
<td>Part #66</td>
<td>8</td>
<td>0.1%</td>
<td>99.6%</td>
<td>Steel</td>
<td></td>
</tr>
<tr>
<td>Part #61</td>
<td>7</td>
<td>0.1%</td>
<td>99.7%</td>
<td>MRD</td>
<td></td>
</tr>
<tr>
<td>Part #60</td>
<td>6</td>
<td>0.1%</td>
<td>99.8%</td>
<td>MRD</td>
<td></td>
</tr>
<tr>
<td>Part #47</td>
<td>4</td>
<td>0.1%</td>
<td>99.9%</td>
<td>2-pc MRP</td>
<td></td>
</tr>
<tr>
<td>Part #65</td>
<td>4</td>
<td>0.1%</td>
<td>99.9%</td>
<td>2-pc MRP</td>
<td></td>
</tr>
<tr>
<td>Part #48</td>
<td>2</td>
<td>0.0%</td>
<td>100.0%</td>
<td>SF</td>
<td></td>
</tr>
<tr>
<td>Part #64</td>
<td>1</td>
<td>0.0%</td>
<td>100.0%</td>
<td>Steel</td>
<td></td>
</tr>
<tr>
<td>Part #53</td>
<td>1</td>
<td>0.0%</td>
<td>100.0%</td>
<td>2-pc MRP</td>
<td></td>
</tr>
<tr>
<td>Part #63</td>
<td>0</td>
<td>0.0%</td>
<td>100.0%</td>
<td>Zero demand</td>
<td></td>
</tr>
<tr>
<td>Part #62</td>
<td>0</td>
<td>0.0%</td>
<td>100.0%</td>
<td>Zero demand</td>
<td></td>
</tr>
<tr>
<td>Part #51</td>
<td>0</td>
<td>0.0%</td>
<td>100.0%</td>
<td>Zero demand</td>
<td></td>
</tr>
<tr>
<td>Total 6616</td>
<td>Percentage</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MRD Volume</td>
<td>3283</td>
<td>79.5%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MRP Volume</td>
<td>1333</td>
<td>20.5%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- MRD parts up to 80% of total volume
- MRD parts in remaining 20%
4.6.2 Machine Groupings for Single Piece Flow

Now that the overall part families are identified and the strategy to segment the line is established, additional details in the line design can begin to be defined. In particular, the future state identified certain processes to be grouped together for single piece flow. Various techniques, including group technology, production flow analysis, dendogram ordering, and assorted clustering algorithms, were used to try to determine the optimal sequence of machine layout. In the end, a direct clustering algorithm with a heavy dose of practicality proved to be the best method for grouping equipment.

The direct clustering algorithm came from a UTC lean manufacturing course provided by the University of Michigan Center for Professional Development. The algorithm presented was in-turn adapted from Singh and Rajamani.50

The algorithm revealed the most efficient sequence for arranging equipment needed for the finishing operations that follow the initial turning and blade milling. These operations do not contribute significantly to the total processing time or lead time of the rotor cell, but arranging them efficiently and in-sequence is important to creating a flow line that does not have reverse flow and can be managed visually. Given the new sequence, it was determined that a few parts, with their existing manufacturing plan, would not fit the forward-flow objective. These parts will have their manufacturing plans reprocessed such that they fit the machine sequence established.

4.7 Layout of the Lean Flow Line

This section describes the process to design the layout of the new rotor cell and the results. The most challenging aspect of the design process was resolving the competing desires and priorities of the numerous stakeholders. A design is presented that achieves the objectives of segregation of MRD parts from MRP parts, forward flow, and reduced square footage.

4.7.1 Layout Design Process

The design process is very iterative. To facilitate rapid iterations in the design, a set of magnetic cutouts were created for every piece of equipment in the rotor cell. These cutouts were arranged on a blank CAD drawing of the new floor space that was attached to a magnetic white board. Based on feedback, the magnetic cutouts could be quickly rearranged to change the layout of the cell.

The empty floor space for the new rotor cell was created when an existing manufacturing cell was removed from the factory. This space has some very good properties. First, it is located directly across an aisle from the ACM build room, therefore being very close to one of the rotor cell’s customers. Second, it is far removed from other large pieces of machining equipment in the factory that are known to create vibrations in the floor; these vibrations impact the balancing operation in the rotor cell. Finally, the space is longer than it is wide; this is a good shape for creating a flow line. On the other hand, there are a few bad things about the space that had to be dealt with during the line design. One, there is a large area of floor space that has basement restrooms and an electrical room below it – this area of the floor cannot support heavy pieces of equipment like the large lathes or mills. Two, there is a 5-foot by 5-foot
unmovable concrete pillar in the middle of the floor that houses electrical conduits. The layout had to work around these two constraints.

4.7.2 Features of the Layout

The layout was designed with the objective to promote flow, to segregate the MRD parts from the MRP parts, and to have as much visual management of the line as possible. Recall that the parts classified as MRD parts are the aluminum single-piece rotors that have manufacturing processes that do not require reverse flow within the cell. MRP parts, on the other hand, consist of the two-piece rotors that travel back and forth between process steps, incurring reverse flow. The MRP parts also consist of the relatively lower-volume steel and titanium rotors.

4.7.2.1 Part Family Segregation

Segregating the line between MRD and MRP helps ensure that the MRD parts flow through the line quickly. After all, the MRD parts comprise about 80% of the total volume of parts in the cell and will be controlled by kanban. Helping the MRD parts flow through the manufacturing process as quickly and efficiently as possible will greatly improve the overall metrics of the cell and will improve the ability of the ACM’s and air conditioning packs to deliver on-time. Of course, the MRP parts should not be ignored, but it is important to focus initially on the MRD parts in order to realize substantial improvement for the cell as a whole. Figure 33 shows a picture of the layout. An aisle through the center of the cell segregates the MRP side of the line from the MRD side of the line.
4.7.2.2 U-Shaped Cells for Single-Piece Flow

Each side of the layout consists of “mini u-shaped cells.” These are the single-piece flow cells that were in-part determined by the clustering analysis. As an example, there is a mini u-shaped cell that contains a deburr workbench, followed by a hone, small lathe, and O.D. grind. Figure 34 shows an enlargement of the MRD side of the line and its five mini-cells. The intent is that each part’s manufacturing plan will be revised to make the operations within any mini-cell a combined operation. That way, when a batch enters a mini-cell, the batch will be processed single-piece through the equipment in the cell. This is a major improvement to the batch-and-queue process of today that leads to inventory accumulating between each individual process step.

4.7.2.3 Visual Management and Inventory Control

The aisle through the center of the layout serves to give the foreman and the operators visual management cues for the line. The foreman can see all areas of the line and keep in contact with all his operators by walking down this single aisle. This vastly improves communication and makes it immediately apparent when a production issue arises in the line. Contrast this to the existing layout in Figure 26. In the existing layout the foreman has a very difficult time keeping track of materials, priorities, and sometimes even the operators!

Controlling inventory is managed through deliberate features in the cell. Material racks, which are located throughout the existing rotor cell, are only allowed on the aisles of the proposed cell, as shown in Figure 34. The racks are specifically for incoming material only. Therefore, operators and the foreman will have a visual signal when work arrives at any of the mini-cells. After the batch is completed, the operator will be
responsible for delivering the batch to the next operation’s incoming material rack. Where there is a shared resource, such as the glass bead peen operation, the incoming material rack will be designated as a FIFO lane. All this means is that the rack will likely have two segregated incoming areas: one for MRD batches, and one for MRP batches. There will be standard work in place to tell the operator how frequently to pull from one area versus the other, as determined by the forecasted volume of parts from the MRD line and MRP line.

Production on the MRD side is triggered through the use of kanban. The future state map shows that the kanban card travels from finished goods inventory to the supermarket ahead of the blade mills. The supermarket of semi-finished inventory and a visual work board to hold the kanban signals will be located near the mills. This placement facilitates visual management, as the foreman and the operators can readily see the kanban signals when they arrive.

Likewise, a second kanban system is used to withdraw raw material in order to refill the supermarket with rotors that have been turned in the lathes. The visual work board to hold these kanban signals is co-located with the raw material. The location of raw material, the supermarket, and finished goods are shown in Figure 33.

4.7.2.4 Shared Equipment

The MRD side of the line contains the majority of the shared equipment. This includes equipment such as the glass bead peen machines, the balance machines, the spin machines, and the marking and inspection workbenches. Regardless of whether a part is MRD or MRP, it will flow into these pieces of equipment if required.
New to the rotor cell is a fluorescent penetrant inspection station. Today, the rotors have to leave the rotor cell to go to a shared FPI area. This area is considered a major bottleneck for the factory as a whole. Placing a dedicated FPI area into the rotor cell will not only help reduce lead time for the rotors, but will help reduce lead time for other parts in the factory that receive fluorescent penetrant inspection. The shared equipment is labeled in Figure 33.

4.7.2.5 Forward Flow through the MRD Line

The equipment on each side of the line was arranged to promote forward-only flow of parts. The MRD parts will benefit the most from this arrangement, as they do not have operations that go back and forth between pieces of equipment. Figure 35 shows the product flow for Part #1 in the new cell. Contrast this to the lack of product flow that characterizes the existing rotor cell, as shown in Figure 26.

4.7.2.6 Reduced Cell Square Footage

The proposed rotor cell occupies about 12,600 square feet. This is a reduction of about 2,400 square feet over the existing rotor cell. Note that the proposed cell includes about 520 square feet for equipment (additional glass burr and FPI area) that is not included in the existing cell. Therefore, on an equal equipment basis, the reduction is actually closer to 3,000 square feet.

The internal overhead rate charged to manufacturing cells is about $20 per square foot annually. Therefore, a reduction of 2,400 square feet will lower overhead costs charged to the rotor cell by about $48,000 per year.
Figure 33: New Rotor Cell Layout

New rotor FPI area (shared between MRP and MRD)

Shared Resources: Balance, Spin, Glass Bead Peen, Mark, Inspect

Finished Goods

Supermarket

Small lathe

Large lathe

MRP Side

MRD Side

Aisle
Figure 34: Mini U-Shaped Cells on the MRD Side

Incoming material racks

Bridgeport mill, tumble, six-spindle drill

Deburr, Hone, Lathe and OD Grind

Balance and Spin

Incoming FIFO racks

Glass bead peen

Inspect, Mark and Assembly
Figure 35: Product Flow for Part #1 in the New Rotor Cell

1) Draw raw materials
2) Mark raw materials
3) Turn
4) Supermarket
5) Mill
6) CMM / Inspect
7) Secondary process
8) Secondary process
9) Secondary process
10) Secondary process
11) Secondary process
12) Secondary process
13) Secondary process
14) Secondary process
15) Secondary process
16) Secondary process
17) Secondary process
18) Deliver to FG
4.7.3 Desires of the Stakeholders

Each stakeholder involved with the rotor cell had an interest in seeing the layout designed in some particular way. Sometimes, the interests competed. This made developing the layout occasionally challenging. This section will discuss some of the major competing desires and how (or if) they were resolved.

In general, the rotor cell operators were interested in keeping the status quo. While they were not opposed to the move in general (and, in fact, some were very impatient to get the move underway), they more or less wanted to pick up the existing cell and place it in the new area mostly as is. Where they wanted change, it was often to ask for more space.

Management, on the other hand, wanted to move to “less”. Less space, in particular, was an often-heard demand. Their reasoning was sound in that each square foot of space occupied by a cell gets charged to that cell in the form of overhead at a rate of $20 per year. Reducing the square footage of the rotor cell therefore reduces the standard cost of the parts and makes the Windsor Locks rotor cell more cost competitive and less likely to be outsourced. To achieve this not only means squeezing the existing equipment closer together, but eliminating as much equipment as possible. The vast majority of equipment in the rotor cell actually consists of cabinets, benches and racks, not machinery. So the desire to reduce square footage can be achieved by reducing these non-essential pieces of equipment as opposed to machinery.

Another desire of management was to create a cell that competes visually with those in Asia. Many of Hamilton Sundstrand’s Asian facilities are seen as world-class. There is tremendous pressure to raise the standard in Windsor Locks to that of Asia.
What this translates into is minimal distance between machines, machines that are aligned in straight lines, and a cell that would "look good" during a tour. In practice this means that the u-shaped cells were to be no more than six feet wide. In addition, much of the supplemental equipment such as workbenches and cabinets would need to move out of the u-shaped cells to achieve this visual state. Most times, this equipment would have to be relocated behind the machines.

Of course, the desires of operators and management often conflicted. The operators, when presented with the goal to move cabinets and benches behind the machines, vehemently objected. Their opinion was that this supplemental equipment was needed at the machines to hold gages, fixtures, and tools, especially since the cell is mixed-model and repeated setups are required. They frequently referred to Hamilton Sundstrand's evolution over time of going from crib-held gages and tooling to point-of-use gages and tooling. Anything that took their tools or gages away from point-of-use was seen as wrong.

Management's response to this was that over time, everything has become point of use, including those tools or fixtures that are used once a month or once a year. What management fundamentally wanted was a rationalization of what must be in the cell for point of use and what can be outside the cell but still close-by.

The team creating the layout, which consisted of the foreman, the manufacturing engineer for rotors, and the author, was often stuck in the middle of this debate. We realized we needed the operators' support if implementation was to be successful, but also that nothing would even begin without management's ultimate approval of the layout. Both sides had valid arguments, and unfortunately there was little we could do to
proceed on the issue, since implementation of the line move was not launched during the internship due to higher-level strategic issues surrounding the real estate initially allocated for the new rotor cell.

In the end, a layout was created that places the equipment into six-foot cells, but the layout includes basically all the benches and cabinets that exist today. Little was identified as surplus or positioned behind the machines. This is a tradeoff and it is in no way suggested that this is an ideal or optimal layout. It is simply one layout from an infinite number of choices. By the end of the internship provisional agreement was given by management to the layout, but no equipment moves had been initiated.

Section 4.7 presented the process and results for creating the layout for the lean flow line. A layout was presented that achieved three objectives: 1) segregating the rotors into two families to promote flow, 2) creating a layout that did not allow reverse flow for the MRD parts, and 3) reducing square footage of the cell. The layout, however, probably did not achieve each stakeholders' individual objectives, in particular the reduction of cabinets and workbenches in the cell.

The next section presents processes used to evaluate the other element of the lean flow line – the design of the “operating system.” The operating system includes variables such as batch sizes and product routing choices that can have a profound impact on the performance of the cell. The operating system also includes the production strategy, such as where strategic supermarkets or FIFO lanes should be located so as to segregate processes, and whether kanban signals should be used to trigger production. Although
many of these decisions were established when the future state map was created, their impacts have not been quantified or measured to determine their potential benefits.

4.8 Introduction to Simulation

"Experience is an expensive school."

Benjamin Franklin

The operating system and the layout progressed simultaneously. As the design of the operating system began, it became immediately clear that the line is a complex environment involving many variables. From the demand of each part number, to the routings of each part, to the batch sizes, to the shift structure, there are numerous variables and unknowns that may not have obvious consequences based on the choices made. Compounding the problem is the fact that the rotor line is mixed-model and relatively low volume. As a mixed-model line, the required capabilities of the line are far beyond that of a line dedicated to a single product. And as a low-volume line, it becomes difficult to ascertain cause and effect relationships between decisions and outcomes because one often has to wait days, weeks, or even months for the outcome to become apparent. During that time, however, many other variables may have changed, leading to confusion.

System dynamics is a field of research and practice that studies the structures and dynamics of complex systems. Unlike systems with simple feedback mechanisms, such as the visual feedback obtained when filling a glass of water, complex systems have multi-loop, multi-state, nonlinear feedback structures.\textsuperscript{51} There are almost always

significant time delays between cause and affect. There is often limited information
and the information one does obtain is often ambiguous. The scale and complexity of
the problem is often beyond human comprehension, literally. And our mental models
of how systems behave frequently rely on the same heuristics that are used to judge
simple causal relations.

While the rotor line may not have the same level of complexity as, say, the state
of the US health care system, it is nonetheless a complex system. Modeling the system,
such that it can be understood and such that the effects of various choices can be explored
in a virtual world, helps us design a system that is likely to succeed after implementation.
Although the system dynamics toolset of causal loop diagrams and stocks and flows was
not chosen as the modeling method, a comprehensive discrete-event simulation was
developed to capture the dynamic and stochastic effects of the system. The reader is
referred to Appendix A for a detailed description of the model. The following two
sections provide an overview of the model along with a further explanation of the options
available for blade milling. This explanation is needed to understand the strategic options
available to the cell.

4.8.1 Overview of the Model

A picture of the model is shown in Figure 36. Simul8 Standard was chosen as
the modeling software since the author had prior experience with the package. The user
interface for all inputs and variables is an Excel spreadsheet.
As mentioned previously, the future state map helped realize the vision for decoupling the lathe from downstream operations through the use of a supermarket of in-process inventory. The model is built upon this vision. The objective of the model is to determine batch sizes, product routings, and appropriate inventory levels such that the cell achieves the objectives for on-time delivery and lead time. The variables in the model include the demand profile for each and every part, the lot size ahead of the supermarket separating the lathe and mill, the lot size following the supermarket, and the mill routings chosen for every part number (to be explained).

The model focuses on the initial turning and milling operations. All secondary operations that follow are grouped together with a simple stochastic time delay. The reason for simplifying the model in this way is based on the anecdotal and observed evidence that the downstream secondary operations only comprise two to three days of the total twenty to thirty day lead time. In other words, improving lead time at the lathe and mill will significantly improve the system as a whole, whereas improving lead time downstream of the mill is not as high a priority.

There are 46 individual part numbers that are represented in the model. These are all the parts that go through the aluminum lathe and blade mill whether they are MRD or MRP. If the part number is turned or milled on the aluminum equipment, it is modeled. Nothing is aggregated in the model beyond the simplification of the secondary operations as described above. This allows for the variables associated with each part number to be individually controlled, leading to the model being very precise and accurate.
Figure 36: Picture of Rotor Cell Simulation
4.8.2 A Further Exploration into Blade Milling

Before proceeding further, a more detailed explanation of the options available for blade milling is required. There are actually five mills available for the aluminum rotors. The two fully-automatic Matsuura MAM-72’s were described in Section 4.3.4. In addition to the MAMs, there are two older twin-spindle CNC mills, and a new Okuma mill.

Interviews with various people at Hamilton Sundstrand revealed that part of the justification for purchasing the two Matsuura MAM-72’s included the fact that the standard cost of the parts produced on the MAMs could be reduced to the load and unload time only. The cutting time would not be included in the standard cost of the product since an operator is not required to attend to the machine during operation. And since the machines have zero-changeover time from one part number to the next, no setup time is incurred.

The manufacturing plan for each part includes “prime” and “alternate” milling operations. The prime operation is where the part should be processed under normal circumstances. Since standard cost is reduced for every part that is processed to the MAMs, there is an incentive to make the MAM the prime operation for every aluminum part number. While this doesn’t preclude a part from being milled on one of the other mills, variance is incurred for every part that is machined on an alternate mill thereby raising the measured cost of the product. For instance, if Part #1 is milled on an alternate mill, 38 minutes of unfavorable cutting time is incurred, plus time for setup of the machine (the standard setup for this part number is 30 minutes for the batch of 20).
4.9 Strategic Decision Making through the Use of Simulation

The simulation provides the framework for evaluating various strategic decisions. Among these are the batch size to use through the lathes, the batch size to use downstream of the lathes including through the mills, the routing of each part number at the mills (i.e. whether the part should be primed to a MAM or to an alternate mill), how many pallets of each type to provide at each MAM, and how much inventory to hold in finished goods and at the supermarket. By varying these choices, the effects on on-time delivery, lead time and WIP inventory can be evaluated.

The first strategic decision involves batch size. As described, a large batch size is desired through the lathes to amortize high setup costs. Downstream of the lathes, a smaller batch size should be used to promote flow and reduce queues at the mills. The supermarket of semi-finished goods separates the two. While a smaller batch size downstream of the lathes can potentially increase the cost index of the cell beyond the standard cost since the standard cost is based on a larger batch size, the reality we believe is different. As explained in Section 4.3.2.2 and as seen in Figure 23, this increase in cost is not seen in practice given that the foreman routinely splits off smaller batch sizes out of the MAMs. Again, this is probably due to the fact that the workforce is experienced and is able to work faster than the standards. Therefore, there is probably room within the system to reduce batch sizes in order to reduce lead times and improve on-time delivery without sacrificing product cost.

The second strategic decision is how to route the various part numbers through the choices of mills. Implicitly, routing a part to a mill other than the MAM raises standard cost if that part is currently primed to the MAM. Yet there may be benefits in
the form of reduced lead time, reduced inventory, and improved on-time delivery by more effectively utilizing the full milling capacity of the line. Unfortunately, the simulation was not developed to capture or measure this tradeoff. Yet consider that even the alternate mills are CNC mills and do not need an operator to attend to them during cutting. Yes, the alternate mills need an operator to perform a setup when part numbers change, and yes, the machine is not capable of automatically loading another part when one finishes, but they should not incur cost during cutting time. This is a very important point; there is no real cost justification for routing to the MAMs beyond the time incurred for a setup at the alternate mills.

Therefore, as the simulation was executed to find a preferred set of product routings, it was assumed that any parts that were directed to an alternate mill would have their standard costs revised to delete the time associated with cutting and replace it with load and unload time, just as the MAMs are costed. This means that the choice of product routing should not be contested on the basis of standard cost.

A third strategic decision is which pallets to make available at the MAMs. This decision is, of course, related to which part numbers to route to which mills. Since there are two MAMs, a part that is primed to a MAM needs to have a pallet provided at both machines if it is to be routed to either machine. If a pallet is only provided in one machine, this reduces the flexibility of that part number. Similarly, if more than one pallet is provided in either one or both of the MAMs, this allows more pieces in the batch to be processed sequentially overnight or over a weekend.

The final strategic decision is to determine how much inventory to hold in finished goods and at the supermarket. This decision involves the demand profile,
replenishment lead time, and desired service level. Initially, a guess was made as to the replenishment lead time from the supermarket to finished goods. The maximum customer demand over that time interval was determined, and an equivalent amount of inventory was placed into finished goods at the start of the simulation (with a minimum of one batch of the smaller-downstream size). Likewise, a replenishment interval was assumed for the lathes replenishing the supermarket and the demand over that interval was translated into an equivalent number of larger-upstream batches, with a minimum of one batch. After the simulation was executed, average service level was determined and the actual lead time was used to revise the assumed lead time prediction and revise the calculation for initial inventory.

4.10 Executing the Simulation

The simulation provides for the ability to predict lead time, on-time delivery and WIP inventory given a set of input conditions. Unfortunately, unlike an optimization, it cannot determine the best set of input conditions to minimize or maximize the objective measures. Therefore, human interaction (and guesswork) is required.

In addition, there are a couple of logical and simulation-imposed constraints on the variables chosen. First, because of the way the kanban system will operate, the batch size through the lathe must be a multiple of the batch size through the mill and downstream. For example, producing in a batch of 24 through the lathe means that the downstream batch size can be 24, 12, 8, 6, 4, 3, 2, or 1. Any other batch size would make it very difficult to regulate the kanban system and would ultimately result in leftover pieces of inventory in the supermarket, which is waste. Second, the downstream batch
size must be an even number. This is a modeling issue related to the dual-spindle mills and is explained in Appendix A.

In executing the simulation, there was a basic hypothesis underlying the choice of inputs. This hypothesis was that the MAMs are best suited to working on a large variety of part numbers since they can switch between part types without setup. Contrast that with the twin-spindle machines. These mills are best suited for producing the same part type over and over, as they can mill two pieces at once, and they would not incur a setup penalty as long as the part number does not change.

This was the initial basis for running the simulation -- offload the two highest-volume part numbers to the two twin-spindle mills. However it was soon realized that offloading even these highest-volume parts would still not be enough to relieve the bottleneck at the MAMs. Therefore, based on discussions with the rotor cell manufacturing engineer, it was determined that part families could be created at the twin-spindle mills such that multiple part numbers, of similar design, could be processed at the twin-spindle mills without incurring excessive setup penalties. Setup reduction efforts would probably be required, but the manufacturing engineer was confident that a nearly common setup could be developed such that changeover from one part number to another within the family could be accomplished in about 5 minutes. This was the key breakthrough to the new manufacturing system.

Based on this guidance, the five highest-volume MRD aluminum rotors, along with substantially similar parts in the part family, are directed to the twin-spindle mills with an assumption of five minutes of setup time any time the part number changes. These five parts represent about 43% of the total rotor volume, so this is a substantial
offload from the MAMs. The aluminum rotors that are classified as MRP are directed to the Okuma mill on the MRP side of the line. The remaining lower-volume part numbers are directed to the MAMs. The number of pallets provided at the MAMs is, in most cases, left unchanged from what is available today. In a few instances, where a part number today can only be processed on one MAM because only pallet is available, an additional pallet is provided to the other MAM to increase routing flexibility.

The final decision for batch sizes was to choose a batch of 18 for the lathes, and a batch of six for downstream operations. This is mostly driven by practicality. A batch size of 18 is close to what is used today, and therefore should not be an issue with regards to the ELQ. A downstream batch size of six will help product flow, and it is also close in size to the batches that today are split-off from the MAMs. Therefore, this batch size should not be an issue with regards to downstream setups.

This section presented the final choices that were used to execute the simulation. The next section reviews Chapter 4; while Chapter 5 presents the results of the simulation and discussion of their meaning.

4.11 Review of Chapter 4

Much information was presented in Chapter 4. The chapter began with an introduction to rotors and the rotor manufacturing process. The state of the existing cell was detailed, including the lack of flow created by the layout, the effects of large batch sizes on cell metrics including lead time and on-time delivery, the impacts of highly-variable demand on the cell metrics, and the implications of pallet availability at the primary machining centers.
The chapter continued with the steps needed to create a lean manufacturing system. Value Stream Mapping is fundamental to discovering waste and creating the vision for the future state. The use of ELQ in the cell means that in order to solve the problem of long lead times, a supermarket of semi-finished goods is used to separate the long-setup lathe operation from the downstream operations. Creating flow is facilitated by the new layout, which incorporates cellular design, visual management, and single-piece flow within the cells. While the layout does not satisfy the desires of every stakeholder, it is a workable compromise. Finally, the simulation provides analytical verification that the supermarket strategy with smaller batch sizes will work. It also provides the operational guidance on which parts to route to which mills.
Chapter 5: Results and Discussion

This chapter presents the results of the simulation, including predicted lead time, predicted on-time delivery, and predicted WIP inventory. Also presented is a net present value calculation showing a positive return for the project.

The thesis concludes with a discussion on the importance of system design in a manufacturing environment. Despite the best efforts of operators and managers, much of the performance of a manufacturing system is governed by how that system is designed. It is only through intelligent redesign that improvements will be made.

5.1 Results and Predictions from the Simulation

Based on the batch sizes, choices for product routing, and pallet decisions that were presented in Section 4.10, the simulation predicts large improvements in cell performance. The important metrics for improved cell performance are lead time, on-time delivery, and inventory.

Lead time for the MRD parts is expected to be five days for small rotors and eight days for large rotors. This time is defined as the interval between the instant a kanban signal arrives at the supermarket and the instant that the finished rotor is placed in finished goods inventory. Today, that time is about 25 days. Lead time has been reduced by 66% - 75%. The time to replenish the supermarket (from raw material through the lathes to the supermarket; signaled by a second kanban) is expected to be four days for small rotors and one day for large rotors.

On-time delivery for the MRD parts is expected to exceed 97%. Today, on-time delivery is below 60%. On-time is defined as the instantaneous fulfillment of an order.
Therefore, when a quantity of rotors is desired by either spares or the ACM customer, the rotors will be waiting in finished goods over 97% of the time. If the time-frame for fulfilling the order is extended to three days, the fulfillment rate will exceed 99%.

Work in process inventory, excluding the supermarket and finished goods, will fall in-line with the lead time reduction. Therefore, WIP inventory can be expected to be reduced by 66% - 75%. Assuming the original cell inventory is valued at $695,000 and assuming 25% of that material is raw material and therefore will not be reduced, and assuming a 2/3 lead time reduction, this translates into a one-time reduction in WIP inventory amounting to $350,000.

The consequence of a finished goods and supermarket strategy, however, is that inventory will need to be held in these locations. Once again, the purpose of the finished goods inventory is to help smooth demand and the purpose of the supermarket is to decouple the batch sizes within the line. Unfortunately, it is difficult to accurately predict the amount of inventory that will be needed in these locations. The simulation is not accurate in this regard because it looks across the period of forecasted demand and finds the peak demand from which to calculate the necessary inventory and kanban cards to satisfy demand over the lead time. As was seen, the demand profile is very erratic. In practice, if nothing is done to address the demand profile, the inventory could be built up slightly ahead of the demand dates. The simulation would have us conclude that that inventory is needed for the entire run of the simulation, vastly overestimating the necessary inventory. The best solution, of course, is to address the demand variability. Smoothing the demand profile will go a very long way to reducing the amount of inventory that is needed at finished goods and at the supermarket. Reducing setup at the
lathes would also help the inventory situation, as that would allow small batches at the
lathes and would eliminate the need for a supermarket.

The need for finished goods and supermarket inventory may reduce the value of
the project. On the flip side, however, the project will result in higher probability of the
ACM’s and air conditioning packs to be built and delivered on-time. This will in turn
reduce higher-value inventory requirements in those cells. Therefore, the negative effect
of higher finished goods rotor inventory may be washed out by reduced ACM and air
conditioning pack inventory.

<table>
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<tr>
<th>Table 8: Summary of Cell Metric Improvements</th>
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<td>Existing Cell</td>
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<td>Lead Time</td>
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<td>On-Time Delivery</td>
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<td>WIP</td>
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<td>Finished goods and supermarket inventory</td>
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5.2 Net Present Value

An estimate of net present value for this project exceeds a quarter of a million
dollars over a three-year timeframe. This estimate includes the cost of moving the rotor
cell to create the lean flow line and includes the cost of the LFM internship (even though
this is a sunk cost and technically should not be included in an NPV calculation). It
estimates a productivity benefit of 6% (i.e. reduction in overtime) as a result of the
improvements created by the flow line. And it includes the $350,000 reduction in WIP,
conservatively reduced to about $310,000 to account for unknowns in the supermarket
and finished goods inventory. The discount rate was conservatively estimated to be 25%.
The value of inventory reduction in the ACM cell and pack cell (as a result of being able
to reduce the lead-time padding in the MRP planning system), along with the value of improved on-time delivery, is not included in the NPV calculation. From this standpoint, the NPV might be even higher than a quarter of a million dollars.

5.3 Discussion

John Sterman, one of the leading researchers in the field of system dynamics explains in his book, “A fundamental principle of system dynamics states that the structure of the system gives rise to its behavior.”56 The production distribution game, commonly called the “Beer Game” gives a classic example of how structure almost predetermines outcome. The interaction of player’s decisions with the structure of the game produces dynamics which diverge significantly and systematically with optimal outcome.57

During the course of the internship, the author had the opportunity to administer the Beer Game to many of the managers and engineers in Mechanical Operations. Included were the foreman of the rotor cell, the foreman of the pack assembly cell (the rotor cell’s ultimate customer), the production planner for these cells, and the manager of these three gentlemen. These four participants were intentionally placed on the same team. It was interesting to listen to them explain during the debrief how the events they experienced in the game (stockouts, gluts of inventory, frustration) closely mirrored their own mini supply chain within the factory.

The beer game, with only four levels in the supply chain, is a 23rd order non-linear problem. How can we possibly manage a real production system that is infinitely more complex? The key, of course, is designing the system to remove the sources of complexity, where possible, and to build robustness into the system where this is not possible.

The performance of the rotor line today is a direct consequence of its evolution over time. It is not the fault of the operators or the foreman or the managers that the cell struggles with lead time and on-time delivery; it is simply an outcome based on the structure of the system. To improve the cell, we must change the structure.

This includes changing the physical layout of the area to incorporate cellular manufacturing, adding elements of visual management, leveling and balancing the cell, and integrating quality control and preventive maintenance. Redirecting the high volume rotors to the twin-spindle mills aligns the capabilities of the zero-setup MAMs with the more variable demand of the low-volume rotors. The supermarket strategy allows for the reduction in batch size, giving the cell the ability to produce a wide-variety of part numbers more quickly. All of these actions promote flow. Next, initiate pull in order to produce to demand. These steps will have an immediate and dramatic impact on lead time and inventory. This is a redesigned system. This system reduces time delays by shortening cycle times, and it reduces complexity by making the management of the cell visual and unambiguous for everyone to interpret.

Of course, this is not the end. Much more improvement is possible. But for it to happen, incentives need to be changed. Jonathan Byrnes, Senior Lecturer at MIT, states,

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58 Ibid, 328.
“Changes to product flow require parallel changes to management systems and structures, such as planning, measurement, compensation, and organization.” 59 One of the biggest changes needs to be a move away from traditional cost accounting system with its rigid adherence to ELQ toward an accounting system that promotes lean behavior. Should this not be possible, setup reduction is even more important to giving the cell the ability to produce in small batches without raising standard cost.

To those within Hamilton Sundstrand, while this may seem world-shattering, I end with the words of Thomas Kuhn: “Scientific revolutions . . . need seem revolutionary only to those whose paradigms are affected by them. To outsiders they may . . . seem normal parts of the developmental process.” 60

Appendix A: Detailed Description of the Simulation

A.1 Overview

The rotor simulation was constructed with Simul8 Release 10, Standard Edition. The user interface is provided through an Excel spreadsheet. The objective of the simulation is to predict the effects of batch size and product routing choices on cell performance metrics such as lead time, on-time delivery, and inventory. Stochastic variables include machining times, setup times, and demand profile.

The simulation is very detailed in its representation of production control (via kanban), batch and queue, and the initial lathe and mill operations, but is highly aggregated in its representation of the rest of the rotor production process downstream of the mills. The areas represented in detail are those that comprise the majority of the lead time in the existing system. Improvements in those areas will lead to the greatest overall improvement for the cell.

The simulation was executed with 17 weeks worth of demand data. The demand data is provided on a by-part-number basis. That is, all 46 part numbers are represented uniquely in the simulation. The first four weeks of the simulation are for break-in to get the simulation to steady state. No data is collected during the first four weeks. The simulation operates on a 24-hour, 7 day per week, 3-shift basis. Resources (operators) can be assigned to various roles in any quantity over any of the three shifts.

Figure 37 shows a picture of the simulation. Batches of raw material flow from left to right, going through a lathe and a hone operation (if required) before being stocked in the supermarket. When a kanban signal arrives, a potentially different batch size of product continues though a mill, through the rest of the aggregated manufacturing
process, and is stocked as finished goods. Orders arrive from the right and are matched to finished goods on an individual basis.
Figure 37: Rotor Cell Simulation
A.2 Rules for Batches and Kanban Cards

Orders enter from the right and are matched to rotors waiting in the finished goods inventory. Assume the batch size of product from the supermarket downstream is six, and the batch size through the lathes is 18. As soon as six orders for any given part number are received, a kanban signal is sent to the supermarket. Assuming a batch of six pieces of that part number are on the supermarket shelf, the kanban is matched to that batch and the batch is processed through a mill and through the rest of the process to eventually be stocked on the shelf of finished goods to replenish the six that were ordered. Likewise, once three batches of six of any part number are pulled from the supermarket, a kanban signal is sent to enter the queues ahead of the lathes. A batch of 18 pieces is then processed through the lathes and hone, if required, before being stocked as three batches of six on the shelves of the supermarket. This cycle of withdrawing from the finished goods and supermarket shelves and refilling the shelves is carried-out on an individual part number basis.

Note that the batch size through the lathes must be a multiple of the batch size through the mills and rest of the process. For example, the lathe batch size of 18 is a multiple of the mill batch size of six. This method of operation ensures that the kanban signals and number of batches will balance.

A.3 Turning and Honing Operations

Figure 38 shows a picture of the area of the simulation that deals with turning and honing. Production is initiated when a kanban signal arrives at the queue in the left edge of the picture labeled “Work Wait Board.” As mentioned in the section above, this
happens when a predetermined number of batches are withdrawn from the supermarket. The work center called “Mark and Dispatch” takes the signal as input and releases a full batch (assume 18 pieces) of parts with the appropriate “labels.” Labels carry identifying information about the parts, such as the part number and routing information collected from the Excel spreadsheet. The work center, based on the label that specifies whether the rotor is a large or small rotor, then directs the 18 pieces to either the queues for the large or small lathe.

**Figure 38: Simulation Showing Two Lathes, Hone, and Supermarket**

Upon arrival of a batch the machine has to be setup. Timing information for the setup (and all other timing information) is contained in the Excel spreadsheet, and is based on the standards. The simulation looks up the time required for the setup based on the part type. Whenever the part type of the next piece in queue is different from the part type of the piece just completed, a setup will be conducted.
The operation of the lathes is rather complicated, but is modeled exactly. The lathes are dual-chuck machines and are capable of machining two pieces at once. Imagine a piece of bar stock. Both the right side and the left side of that bar stock need to be machined. At the start of a batch the operator will load the piece into the left chuck. After hitting start, the tools will cut the features on the right side of the piece. After cutting, the operator cleans away any chips and cleans the opposite chuck which is currently vacant. After hitting start, the lathe automatically transfers the piece from the left chuck to the right chuck. The operator then cleans and loads the left chuck with a new piece of raw material. Upon hitting start, the lathe simultaneously cuts the left features on the piece that is in the right chuck, and the right features on the piece in the left chuck. When the lathe is finished, the operator removes the finished piece from the right chuck, visually inspects it and he may measure a few key dimensions, then hits start to initiate the transfer of the other piece from left to right. During the transfer and cutting operations, the operator will inspect other dimensions on the finished rotor. From here to the end of the batch, the sequence of loading a new piece into the left turret, cutting two pieces simultaneously, removing the finished piece from the right turret, transferring the half-finished piece from left to right, and inspection is repeated.

The model is accurate in the fact that this twice-cut behavior is captured. In addition, the model accurately represents the unique behavior that happens at the start and the end of a batch. At the start of a batch, it takes a cycle before the two-piece steady state is reached. At the end of the batch, unless the next batch is of the same part number, the last cycle will be run with only one piece. This verification of checking to make sure that a piece from the next batch in queue is of the same part number if it is to be loaded
with the last piece of the first batch, is captured in the model. And as mentioned, if the next part type is different, a setup will be conducted.

The model includes operators as resources. The load, unload, and inspect operations require an operator. While the machine is cutting, on the other hand, the operator is free (to perform inspection, to hone, or be idle).

The timing information for every process in the simulation is contained in the Excel spreadsheet. The average loading and unloading time was determined through observing the lathe operators. The loading time is typically short, on the order of 12 seconds, and is given a fairly tight distribution in the model. The unloading time, which includes cleaning the chucks of any chips and visual inspection of the finished piece, is longer and has a wider distribution. The cutting time is assumed to be 90% of the standard time, and is given a normal distribution with standard deviation equal to 25% of the mean. Inspection is assumed to be one minute, but has a wide distribution (up to 10 minutes in 2% of the cases) to reflect the fact that the initial pieces coming off the lot are inspected with more rigor.

Following inspection, the piece will move to one of two locations. If honing is required by the part number's manufacturing plan (and is input in the Excel spreadsheet), the part will go to the queue for hone. The hone operation requires an operator, so it will take the piece from the queue when an operator is available. Note that this is essentially single piece flow between the lathe and hone. The batch of 18 is not collected then processed through the hone; instead, as soon as a piece and an operator are ready, the hone operation can commence.
After hone, or if hone is not required, the piece will go to the queue ahead of "Collect and Inspect". Here, batching is accomplished. Work will not proceed at the Collect and Inspect workstation until all pieces in the batch of 18 are in the queue. Although it is a misnomer, the Collect and Inspect operation really reflects a transportation time delay. Out of this step the batch is re-broken into individual pieces and then immediately re-collected into batches of six pieces by the operation labeled "Batch". This step places three batches of six parts on the supermarket. This ends the lathe and hone area of the simulation.

A.4 Semi-Finished Supermarket and Blade Milling

Many of the strategic choices in the rotor cell are associated with the blade mills. Figure 39 shows the part of the simulation associated with milling. As mentioned in Section 4.8.2, there are actually five mills available for the aluminum rotors. There are two fully-automatic Matsuura MAM-72’s, two twin-spindle CNC mills, and a newer Okuma mill for the MRP aluminum rotors.

Each part type is given routing information in the Excel spreadsheet. A part can be routed to one specific MAM, either MAM depending on queue length, a twin-spindle mill, or the Okuma (MRP) mill. Withdrawal from the supermarket is initiated when a kanban signal arrives at the queue labeled “Work Wait Board 2” which is located just under the supermarket. When the signal arrives, it is matched to a batch of six parts waiting in the supermarket. The batch is then routed (distributed) based on the routing information carried in a label, through the various “Dist” workstations to the appropriate mill queue.
The model accurately represents the behavior of the MAMs. It includes the pallets available for each part type at each of the MAMs, and accurately limits the capacity of rotors that can be loaded into the mill while awaiting cutting. There is a queue ahead of each MAM that represents parts waiting to be loaded into the machine. There is also a queue located between the loading operation and the cutting operation which represents parts that are physically on pallets and are loaded in the machine.

In order for a rotor to be loaded, that is, transferred from the first queue to the second, a pallet of matching type has to be available. If two pallets are available for a given part type, then at most two parts will be loaded in the machine. The information on number and type of pallets available at each MAM is, of course, loaded through the Excel
spreadsheet. The pallets are uniquely represented in the model and get “recycled”
through the backwards-facing loop shown at each MAM.

Like the lathes, an operator is required for loading and unloading the MAMs, but
is not required to attend the cutting operation. There is no setup time at the MAMs when
a part number changes. The times for loading and unloading were obtained by
interviewing the operator. An average of five minutes is given for loading a part and four
minutes for unloading it, with standard deviations equal to 25% of the mean. The cutting
time in the simulation equals the standard time with no distribution.

The two twin-spindle mills, one Matsuura and one Bostomatic, are manual setup
and load. That is, an operator is required to change a setup and to load or unload the
rotors from the machine. The machines are fully CNC, so like the MAMs, the operator
does not need to monitor the machine during chip cutting. If the routing label indicates
that a rotor of a certain part number is to go to one of the twin-spindle mills, the entire
batch will be routed to the mill that has the smallest queue. Like the lathe, a setup is
required whenever the part number changes from the part number previously milled.
However, as explained in Section 4.10, the changeover time for the family of parts
primed to the twin-spindle mills is assumed to be only five minutes. The cutting time is
taken from the standard. In general, the time required to mill a rotor on one of the twin-
spindle mills is longer than on a MAM. Two pieces at a time (of the same part number)
are loaded and cut at once since they are twin-spindle machines. In order to reduce
complexity and avoid additional logic in the simulation, this means that the batches in the
supermarket and downstream must be an even number. Otherwise there would have to
be logic to prevent the situation where one part of one type is loaded with one part of
another type. With an even number batch, two pieces are assured to be of the same part type.

The Okuma MRP mill is similar to the twin-spindle mills, but it is single-spindle. Load, unload, and the need for setups are the same, but the setup time is not assumed to be 5 minutes.

Following exit from a mill, the piece goes to the queue ahead of “Rest of Process”. Here, it waits until the batch of six is ready. Upon arrival of six pieces of the same part number, the batch proceeds to the rest of the process.

A.5 Secondary Operations

Prior to being stocked as finished goods, all rotors have to complete the secondary finishing operations such as deburring, honing, grinding, etc. As mentioned, these operations are not explicitly defined in the model, but are rather simplified into one process step. The queue in the figure below randomly assigns a delay of between 2 ½ to 3 ½ days to represent the time these processes usually take. The workstation “Stock FG Inventory” takes the finished batch of six and splits it into six individual pieces to stock on the finished goods shelf.

Figure 40: Secondary Processes
A.6 Order Fulfillment

Seventeen weeks worth of actual weekly forecasted demand is included in the Excel input spreadsheet. The demand data is provided on a by-part-number basis. In any given week in the simulation, the demand for total number of parts (i.e. the sum over all individual part number's demand) is used to calculate an overall interarrival time with an exponential distribution. The work center element called “Create Orders” in the figure below randomly generates an order based on this interarrival time.

An order represents the request of a specific part number by the customer. In other words, when an order is generated it is not generic, but is rather for a specific part number rotor. Therefore, the work center also assigns a label to each order to represent the part number. The “Fulfill Order” work station looks to match the order with a rotor of identical part number.

If the rotor is sitting in the Finished Goods Inventory, it is instantaneously matched to the order and they leave the simulation. If the rotor is not in the Finished Goods Inventory, the order waits in the Queue of Orders until the rotor arrives. A rotor is considered to be delivered “on-time” if the order does not have to sit in queue. That is, the rotor is available on the shelf when an order is generated.

Figure 41: Order Fulfillment
A.7 A Note on Large Rotors

Large rotors complicate the simulation in that they can require two passes through the lathe and mill – a roughing pass to hog out material, and a finishing pass. This gets especially complicated with the supermarket strategy, two different batch sizes, and the objectives of standard cost. The lathes, of course, favor larger batch sizes while the mills favor smaller batch sizes. The large rotors have to be turned, milled, turned, and milled. Therefore, what should be the batch size throughout these operations, and when do the parts get stocked on the supermarket?

A number of options are available, but after considering all it was determined that only one is logistically feasible. This option is to rough the raw material in the lathe with a large batch size to amortize the setup. As soon as six pieces are off the lathe, the smaller batch proceeds directly to the mill queue, bypassing the supermarket. The pieces are roughed through the appropriate mill, regrouped into a batch of six and are redirected as a batch of six back to the queue for the large lathe. For the finishing pass through the lathe, the batch size will be six. After the finish turn, however, the batch of six proceeds to the supermarket to wait for a kanban signal before proceeding the last time through the mill and continuing. This procedure raises the standard cost of the large rotors during the finishing pass, but it is the only way to reap the benefits of flow (small batch size) through the mills while not making the logistics of coordinated batches out of control.

To add to the complexity, it was determined that the large rotors are unsuitable for the twin-spindle mills. The large rotors cannot be processed to the twin-spindle mills because these machines are older machines with lower reliability. Due to tolerancing issues, it is not possible to rough the rotor on one mill and finish it on another. Therefore,
if a twin-spindle mill broke down after roughing a batch of parts, that batch would have no choice but to wait for the mill to be repaired before they could be finished. This was deemed unacceptable. Therefore, the large rotors are only routed to the MAMs or to the MRP mill. All of the logic as to whether a part is large or small, and if it is large whether it is going through the lathe on its first trip or second, is included in the model.

A.8 Resources

Resources (operators) are used throughout the model at work stations that require a person to perform the operation. Various types and quantities of resources were experimented with. In the end, it was determined that a single resource on the first shift should be dedicated to the small lathe since the small lathe has a very high volume of parts through it and requires staffing all the time. The other operations, including the large lathe, hone, and all five mills, can be staffed with two operators on the first shift, and one operator on the second shift.
Appendix B: Value Stream Mapping Symbols

Manufacturing Process

Shared Manufacturing Process

\[
\begin{align*}
p/t &= 5 \text{ min/pc} \\
\text{c/o} &= 20 \text{ min} \\
2 \text{ shifts} \quad &\text{yield} = 100\% \\
rel &= 95\%
\end{align*}
\]

Data box

Inventory

Truck Delivery

PUSH Arrow

FIFO

First-In-First-Out Sequence

FLOW

Operator

External Source (Customer/Supplier)

Electronic Information Flow

“Go see” Production Scheduling

Supermarket

Pull Withdrawal

Production Kanban

Signal Kanban

Withdrawal Kanban

Kaizen burst
Bibliography


